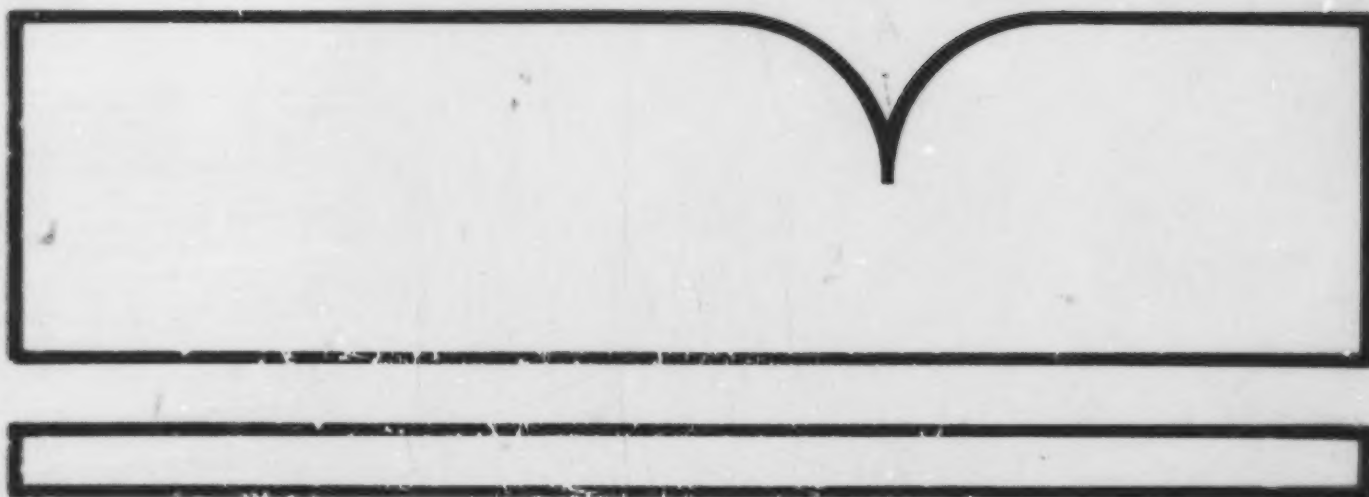


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FEASIBILITY OF ULTRASONIC AND OTHER METHODS FOR DIRECT
MEASUREMENT OF CONDENSER BIOFOULING

Radian Corp.
Austin, TX

May 84



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FEASIBILITY OF ULTRASONIC AND OTHER METHODS
FOR DIRECT MEASUREMENT OF CONDENSER
BIOFOULING

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ABSTRACT

This project involved literature review and laboratory studies of the potential of ultrasonic and other methods for in-situ measurement of biofouling on heat transfer surfaces (e.g., tubes) of electric utility steam condensers. Detection of the presence of biofouling in steam condensers is important for maintaining maximum heat transfer efficiency and minimizing the addition of chlorine (used to control biofouling) in order to meet discharge regulations. A literature search was made of current industrial practices and research underway to develop both indirect and in-situ methods of biofouling measurement. Most methods are not sensitive enough to detect biofouling in its early stages, while it is easiest to control. A preliminary assessment indicated that these shortcomings might be avoided by the use of ultrasonics. An evaluation of the sensitivity of ultrasonic methods for this application confirmed the possible feasibility of this approach, but a number of questions were raised because of the lack of testing with the specific equipment needed, as well as the lack of acoustic property data on biofouling material. Samples of biofouling material were obtained from an operating, commercial condenser and "grown" in the laboratory. The acoustic properties of the material were measured as being close to those of water, but possibly different enough that biofouling measurement via ultrasonics might be feasible with further equipment improvements.

CONTENTS

<u>Section</u>	<u>Page</u>
1. INTRODUCTION	1
1.1 TECHNICAL BACKGROUND.	3
1.2 CONCLUSIONS/RECOMMENDATIONS	4
2. SUMMARY OF LABORATORY STUDIES.	5
2.1 SAMPLE COLLECTION AND BIOFOULING GROWTH	5
2.2 ACOUSTIC CHARACTERIZATION OF BIOFOULING	8
2.2.1 Test Method.	8
2.3 SUMMARY OF RESULTS.	18
2.3.1 Acoustic Impedance of Biofouling Material.	20
3. DETECTION OF BIOFOULING BY ULTRASONIC TECHNIQUES	22
4. CONCLUSIONS	25
REFERENCES	27
APPENDIX A: TASK 1 SUMMARY REPORT: LITERATURE REVIEW OF CURRENT METHODS FOR DETECTING CONDENSER BIOFOULING.	A-1
APPENDIX B: TASK 2 SUMMARY REPORT: PRELIMINARY EVALUATION OF SENSITIVITY AND FEASIBILITY OF ULTRA- SONICS FOR CONDENSER BIOFOULING DETECTION.	B-1

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LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
2-1 Test equipment used in acoustic characterization of biofouling materials.....	9
2-2 Biofouling sample in test fixture.....	11
2-3 Ultrasonic pulses received with test system in pitch-catch mode.....	14
2-4 Superimposition of received pulses p_1 and p_5	15
2-5 Ultrasonic pulses received with test system in pulse-echo mode.....	16
2-6 Superimposition of received pulses r_1 and r_5	17
3-1 Detection of biofouling by reflection from slime layer interfaces (pulse-echo method).....	23

LIST OF TABLES

<u>Table</u>	<u>Page</u>
2-1 Sound Speed Measurement Results.....	19
2-2 Relative Acoustic Impedance of Biofouling Materials.....	21

SECTION 1

INTRODUCTION

Steam electric power plants utilize condensers to remove heat from and condense low pressure steam following expansion in the steam turbine. The cooling-water side of the condenser can be operated in either a once-through or recirculating mode. In either case, large quantities of cooling water are pumped through the condensers. Cooling waters may contain various materials that can form inorganic and/or organic deposits (referred to as "fouling") on condenser tube walls and water boxes. There are four types of fouling that can occur:¹

1. Fouling by scale formation resulting from precipitation of inorganic salts such as calcium carbonate, calcium sulfate, or silicates.
2. Fouling resulting from corrosion when insulating layers of metal oxides are formed on tubes.
3. Fouling due to adherence of particulate matter (e.g., silt, clay) on tube surfaces.
4. Biological fouling resulting from the development of biological growth on tube surfaces.

These fouling deposits reduce the heat transfer from the condensing steam to the cooling water. The reduced condenser heat transfer results in a reduction of a power plant's generating capacity.

It is estimated that in 1977 all types of condenser fouling resulted in efficiency losses amounting to \$100 million in the United States utility industry alone.² This staggering cost indicates the importance of controlling fouling accumulation in condensers.

There are several approaches to controlling the various types of condenser fouling. An important part of these approaches is detecting the presence of the fouling materials before significant deterioration of condenser heat transfer efficiency occurs. This study addresses the detection of biofouling on heat transfer surfaces in industrial steam condensers. Detection of the presence of biofouling materials in condenser tubes is critical in monitoring heat transfer efficiency. It is also crucial in minimizing the chlorine residual required to control the biofouling and meet current discharge regulations.

The project consisted of three tasks.

1. A literature search of current industrial practices used to detect biofouling condensers.
2. A determination of the sensitivity of ultrasonics for detection of biofouling and the feasibility of this approach.
3. A laboratory study to determine the acoustic characteristics of biofouling materials.

The main body of this report presents a summary of the significant findings of the third task: Tasks 1 and 2 are described in detail in Appendices A and B. The third task included the following subtasks:

1. Acquisition of biofouling samples from an existing power plant.
2. Determination of the acoustic impedance of the biofouling materials.

The goal of the third task was to determine whether the acoustic impedance of the biofouling material is different from the acoustic impedance of

water. This difference in acoustic impedance will determine whether the ultrasonic detection of biofilm is feasible. This task did not attempt to simulate condenser operating conditions, online detection techniques, or the acoustic properties of a complex biofouling matrix containing inorganic contaminants and silt. It was a simple laboratory test using state-of-the-art ultrasonic equipment to determine the acoustic properties of biofouling (100 percent biological) material relative to water.

1.1 TECHNICAL BACKGROUND

Ultrasonic technology uses vibratory sound waves at frequencies above those within the hearing range of the average person. It is used extensively in nondestructive testing of materials to detect surface and subsurface flaws, measure thickness, and determine the extent of corrosion. In these applications, ultrasonic waves are introduced into a material and are reflected at interfaces (material boundaries). The degree of reflection depends largely on the differences in the physical state of the materials that meet at an interface and, to a lesser extent, on the specific physical properties of the material, especially acoustic impedance and ultrasonic attenuation.

The data compiled from available literature in Task 2 of this project indicate that ultrasonic technology has a potential for detection and measurement of biofilms less than 50 μ m thick. This is the critical thickness above which cooling water flow and heat transfer in condensers are impeded. The limited material is very similar to water. This will make detection of biofilms difficult due to the low degree of reflection of an ultrasonic pulse from the biofouling material/water interface.

In order to determine the feasibility of ultrasonic detection of biofouling, laboratory determinations of the acoustic impedance of biofouling material were undertaken. Since the acoustic properties of biofouling material and water are very similar, the test work performed in this task

represents a "worst case" condition for ultrasonic detection of biofilms. The complex biofouling encountered in industrial condensers may be more easily detected than pure biological material due to the acoustic properties of contaminants trapped in the biomass. The investigations are designed to determine if a reflection from the biofouling material/water interface can be detected with state-of-the-art ultrasonic equipment. The conclusions and results of these laboratory investigations will be presented in the remainder of this report.

1.2 CONCLUSIONS/RECOMMENDATIONS

The conclusions of the laboratory acoustic characterization studies indicate that the acoustic impedance of biofouling materials is measurably different from water. Processing of ultrasonic signals in the frequency and dynamic ranges required for biofouling detection is within the capability of current technology. However, hardware has not been specifically developed to meet all the requirements for biofouling detection. It is recommended that a program designed to develop a biofouling detection system for field testing be undertaken. A program for development of this device should include the following tasks:

1. A survey of available manufactured hardware.
2. Hardware acquisition/modification/design as appropriate and acoustic characterization of additional biofouling samples.
3. Laboratory testing in a simulated condenser environment.
4. Field testing in a utility condenser.

The proposed first task will be critical in determining the scope of the subsequent tasks. More detailed discussion of these recommendations are included in Section 4.0.

SECTION 2

SUMMARY OF LABORATORY STUDIES

Task 3 of this project consisted of the acquisition of biofouling samples from a power plant condenser and a determination of the acoustic impedance of these materials. The goal of the sample collection subtask was to obtain representative samples from an existing power plant condenser and if required, to grow additional microorganisms in the laboratory. When sufficient biomass was collected or accumulated, these samples were acoustically characterized using ultrasonic techniques. The details and results of these subtasks are presented in the following subsections.

2.1. SAMPLE COLLECTION AND BIOFOULING GROWTH

In order to conduct the acoustic characterization study on representative fresh water biofouling materials, samples from an operating power plant condenser had to be obtained. These samples were supplied by Public Service Electric and Gas Company's Mercer Generating Station which uses Delaware River water for cooling. This station has been the site of testing of pilot-scale condensers for biofouling measurement and control by the Electric Power Research Institute (EPRI). The station experiences severe biofouling during the summer months.

Biofouling samples collected from different plant sites may not be completely representative of all sites due to many factors such as varying water quality, cooling system configuration, and the amount of inorganic material trapped in the biomass. Detection of only microorganism growths which contain no inorganic contaminants or silt are considered in this task. Since the microorganisms that comprise the living portion of the biofouling materials are common to most power plant situations, biomass grown from the Mercer Generating Station should be representative for the purposes of this study.

Condenser design and operating conditions for the Mercer Generating Station condenser are presented below:

Circulating Water	120,000 gpm (7570 l/s)
Pipe Diameter	84 in (2.13 m)
No. of Tubes in Each Condenser	21,992 -- 10,996 per shell
Diameter of the Tubes	7/8 in (22.2 mm)
Exhaust Steam Temperature	1A - 90°F (32°C) 1B - 88°F (31°C)
Inlet and Outlet Water	Inlet - 65°F (18°C)
Temperature	Outlet - 76°F (24°C)
Condenser Tube Material	18 BWG Admiralty, B-111 304 S.S. in Air Removal Section

The velocity in the condenser tubes is 3.7 ft/(1.1 m/s) which is typical of utility condensers.

The samples were collected by plant personnel during a unit outage. Approximately two quarts (1.9 l) of biofouling samples were collected and frozen prior to shipment. The samples were a conglomeration of biological materials and silt. Since there was not enough biological material in the sample that could be isolated for the laboratory study, a means of growing a sufficient amount of biomass had to be undertaken. To accomodate this effort, 10 gallons (37.9 l) of Delaware River water were also collected and shipped to Radian to ensure that the laboratory growth and nutrient availability were comparable to the power plant cooling water. These samples were collected in May, 1981.

A laboratory apparatus was set up to grow and maintain a healthy population of biofouling microorganisms. It consisted of a 10-gallon (37.9 l) aquarium tank, a plate glass sheet, a circulating pump, aluminum test coupons, and an immersion heater. The glass sheet was placed in the aquarium at approximately a 30° angle. Water in the aquarium was pumped and

distributed uniformly over the surface of the inclined glass plate to provide a flowing water film on the glass plate. Test coupons were attached to the surface of the glass plate to provide the growth and accumulation points for the biofouling materials. An immersion heater was placed in the aquarium tank to maintain the water at 76°F (24°C), which is comparable to the cooling water outlet temperature at the Mercer Generating Station. In order to simulate the utility condenser environment the entire apparatus was enclosed to exclude light. This system was designed to encourage the growth of the microorganisms that thrive under the condenser temperature and nutrient conditions.

In order to compare acoustic properties of biofouling material grown in the tank and pure biofouling (slime) material, several petri dishes containing an agar substrate were inoculated with water from the growth tank. Relatively pure cultures of biofouling microorganisms were grown in this manner. During the acoustic characterization studies, both the pure microorganisms grown in petri dishes and tank-grown biofouling materials, which are an agglomeration of living materials with traces of silt, were evaluated.

The elapsed time required to accumulate sufficient biofouling materials (~100 ml) for the acoustic characterization studies was approximately 3 months. Growth on the aluminum test coupons was extremely slow and had to be abandoned. These coupons were to fit directly into the ultrasonic testing assembly. As a result, samples were scraped from the inclined glass plate and aquarium walls. The attachment of microorganisms to a tube surface may have a significant impact on the detection of a biofilm, but has negligible impact on the acoustic impedance measurements performed in this task.

Three different samples were used in acoustic characterization:

1. A water/biofouling mixture from the growth tank (approximately 50 wt percent water).

2. A filtered biofouling sample from the growth tank.

3. A pure bacterial sample from the petri dish cultures.

These three samples provided a wide range of sample characteristics for which acoustic properties could be determined. The color of the samples ranged from rusty orange for the tank-grown biofouling materials to a milky white for the bacterial cultures grown on petri dishes.

2.2 ACOUSTIC CHARACTERIZATION OF BIOFOULING

Once sufficient biofouling material was grown, the acoustic properties of this material relative to water were determined. The section summarizes the laboratory test apparatus, test methods, and results of this evaluation.

2.2.1 Test Method

Speed of sound in the biofouling material was determined by measuring the time of flight of an ultrasonic pulse through a layer of the material. The configuration of the test equipment used in the laboratory studies is presented in Figure 2-1. A special test fixture shown in Figure 2-2 was used to hold the biofouling material for this measurement.

The test sample was placed in a disk-shaped cavity between the two aluminum delay rods. The sample completely filled the cavity to provide well-defined interfaces between the sample and delay rods. This also controlled the sample dimensions.

During tests, an ultrasonic pulse was transmitted from a transducer on the end of one of the delay rods. The pulse propagated through the delay rod and into the biofouling material sample. The pulse then reflected back and forth between the faces of the disk-shaped sample. At each reflection

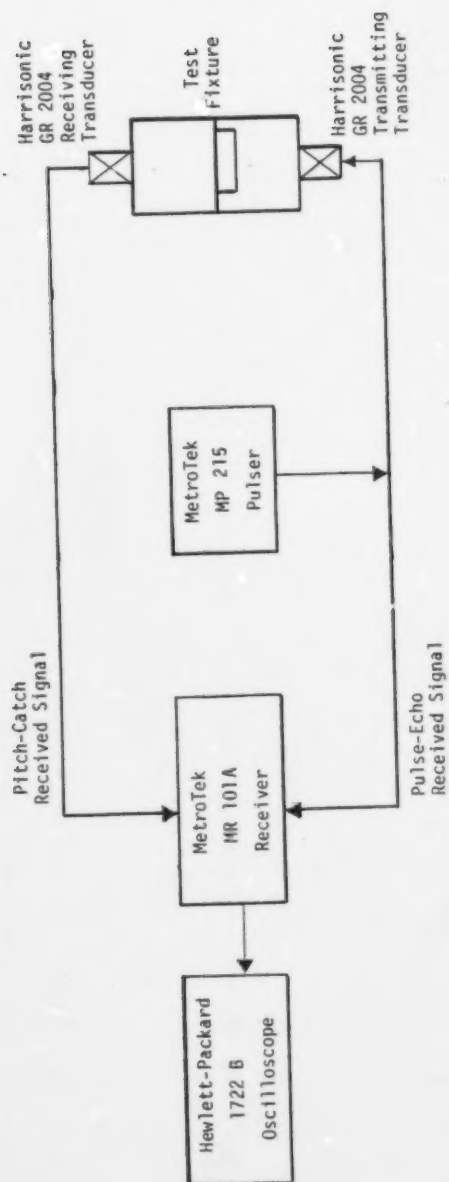


Figure 2-1. Test equipment used in acoustic characterization of biofouling materials.

some of the pulse energy was reflected back toward the transmitting transducer (r_i), and some proceeded through the adjacent delay rod to the receiving transducer (P_i).

The proportions of pulsed energy reflected and transmitted at each interface between the delay rods and the sample are dependent upon the acoustic impedance of the materials. The relative amounts of pulsed energy reflected and transmitted are important in determining the accuracy of an ultrasonic measurement. The relative amounts of energy, reflected (r) and transmitted (t), are defined by the power coefficients (a) as follows:

$$\alpha_{r_{ab}} = \left[\frac{\rho_b c_b - \rho_a c_a}{\rho_a c_a + \rho_b c_b} \right]^2 \quad (2-1)$$

$$\alpha_{t_{ab}} = \frac{\rho_a c_a}{\rho_b c_b} \left[\frac{2\rho_b c_b}{\rho_a c_a + \rho_b c_b} \right]^2 \quad (2-2)$$

$$\alpha_{t_{ba}} = \frac{\rho_b c_b}{\rho_a c_a} \left[\frac{2\rho_a c_a}{\rho_a c_a + \rho_b c_b} \right]^2 \quad (2-3)$$

where ρ is the density of the material, c is the speed of sound through the material and the subscripts a and b indicate the materials at the interface. The product of density and the sound speed through the material, or ρc , is the acoustic impedance of the material. Power coefficients $\alpha_{r_{ab}}$ and $\alpha_{t_{ab}}$ refer to the power reflected at the lower delay rod/sample interface and transmitted into the sample from the lower delay rod as shown in Figure 2-2. The $\alpha_{t_{ba}}$ coefficient refers to the energy transmitted from the sample to the upper delay rod at that interface.

The power coefficients for the aluminum delay rods ($\rho=2.7 \text{ g/cm}^3$, $c = 6.4 \times 10^5 \text{ cm/s}$) and water ($\rho=1 \text{ g/cm}^3$, $c=1.5 \times 10^5 \text{ cm/s}$) are:

$$\alpha_{r_{ab}} = 0.71$$

$$\alpha_{t_{ab}} = 0.29$$

$$\alpha_{t_{ba}} = 0.29$$

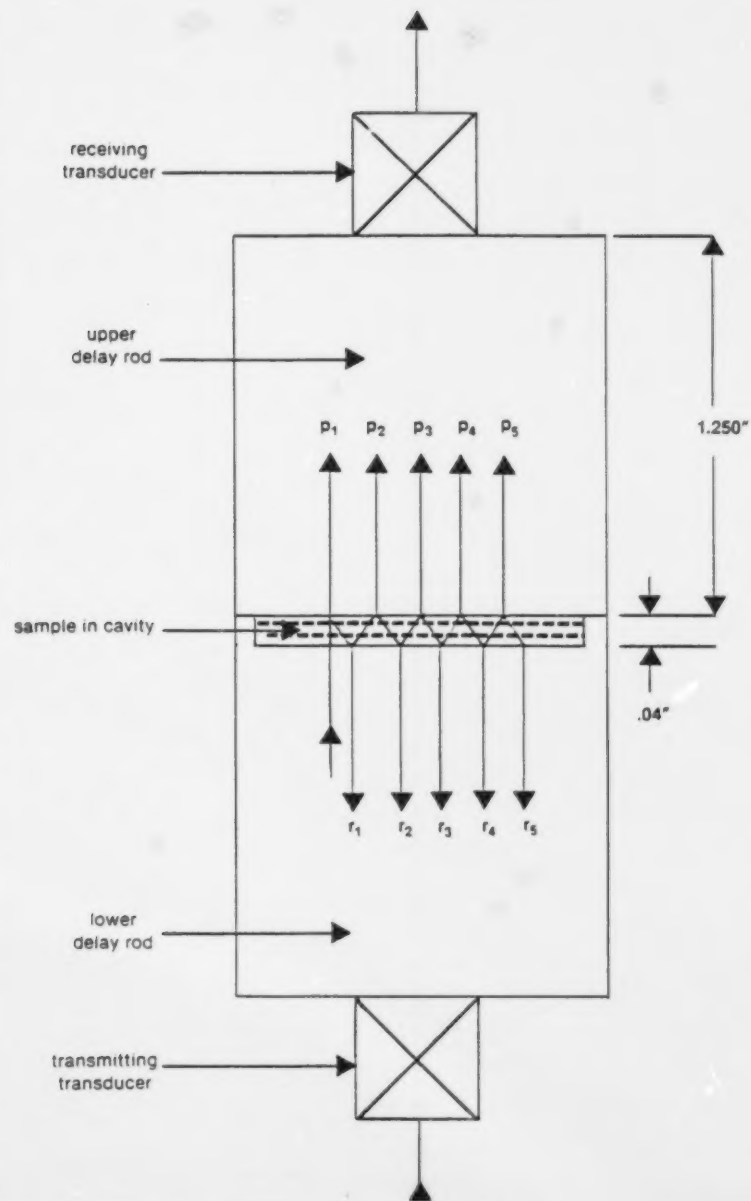


Figure 2-2. Biofouling sample in test fixture.

This indicates that with water in the test assembly, each time the pulse meets the interface between the two materials, 71 percent of the pulse energy is reflected and 29 percent of the energy is transmitted across the interface. Sufficient energy is transferred across the interface from the test material to the delay rods to be easily detectable by transducers at the ends of the delay rods. The successive reflections of the pulse back and forth across the test material can also be easily observed. The acoustic impedances of water and biofouling materials are similar so the calculations above should be applicable to the acoustic characterization of biofouling materials also.

The time delay between reflections may be used to calculate the speed of sound, in the test material as follows:

$$v = \frac{2L}{\tau}$$

where L is the thickness of the sample in the material and τ is the time delay between successive reflections observed at the end of one of the delay rods. The factor 2 results from the fact that a pulse traverses the material twice, once in each direction, between successive observations.

The reflected pulses may be observed at the end of either delay rod. If the transmitting transducer is also used to receive the pulses, the system is said to be operated in pulse-echo mode. If two transducers at opposite ends of the test fixture are used as a transmitter-receiver pair, the system is said to be operated in pitch-catch mode. The system was used in both modes, and the sound speed measurement results for both modes were indistinguishable, as should be expected.

For reasons of experimental accuracy, it was preferable to measure the time delay between the first and last observable pulses rather than between successive pulses. The time between successive pulses was then calculated from the measured multi-phase delay time. The dimensions of the test fixture, as indicated in Figure 2-2, were such that five or six pulses from the

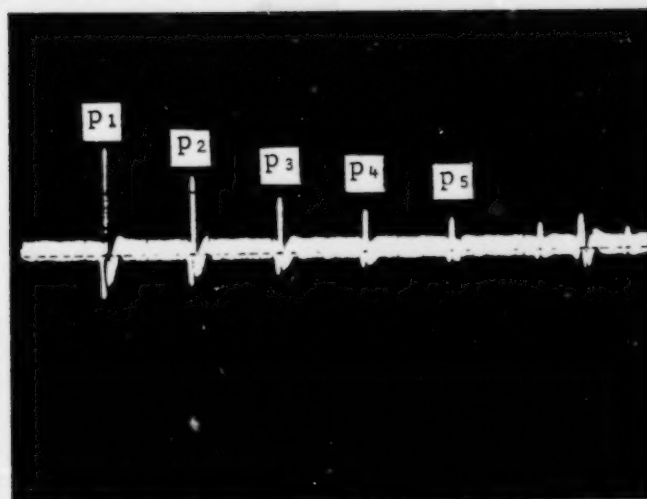
test material could be observed before interfering reflections from the ends of the delay rods were received.

In all the tests, pulses were generated and received using equipment designed for ultrasonic nondestructive testing and inspection of materials. The pulser (MetroTek MP215) generated pulses of approximately 100 nanoseconds (ns) duration. The frequency spectrum of the test signal was therefore a band centered at about 10 MHz. The pulses were received by a MetroTek MR101A receiver and displayed on a Hewlett Packard HP 1722B oscilloscope.

Figure 2-3 shows a typical display when the system was used in the pitch-catch mode. The oscilloscope sweep was triggered by the transmitted pulse. The received pulses designated p_1 , p_2 , p_3 , p_4 , and p_5 are those which have made 1, 3, 5, 7 and 9 transits, respectively, through the biofouling material. The paths for these signals are also shown in Figure 2-2.

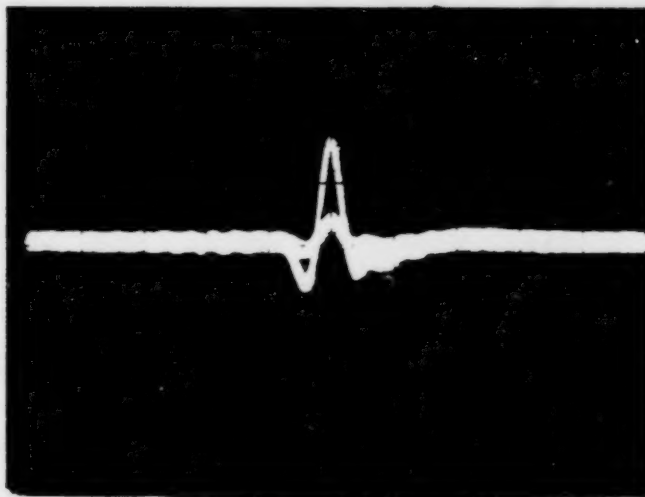
Figure 2-4 is a detail of the p_5 pulse superimposed on the p_1 pulse. The superimposition was done on the oscilloscope, by adjusting the sweep time delay between two traces of the same signal. The time delay required to superimpose p_1 and p_5 corresponds to the time interval between the pulses. Time delays were measurable with an accuracy of about 10 ns. Since the delay time for this case was about 5 microseconds (μs), the accuracy of the measurement was about 0.02 percent.

Similar measurements were made using the system in the pulse-echo mode. In this mode, the transmitting transducer was used also as the receiving transducer. A typical received pulse sequence is shown in Figure 2-5. The paths for the pulses labeled as r_1 , r_2 , r_3 , r_4 , and r_5 in Figure 2-5 correlate with those shown in Figure 2-2. The inter-pulse time delays measured by this method were virtually identical to those measured by the pitch-catch technique. Figure 2-6 shows the superimposition of pulses r_1 and r_5 .



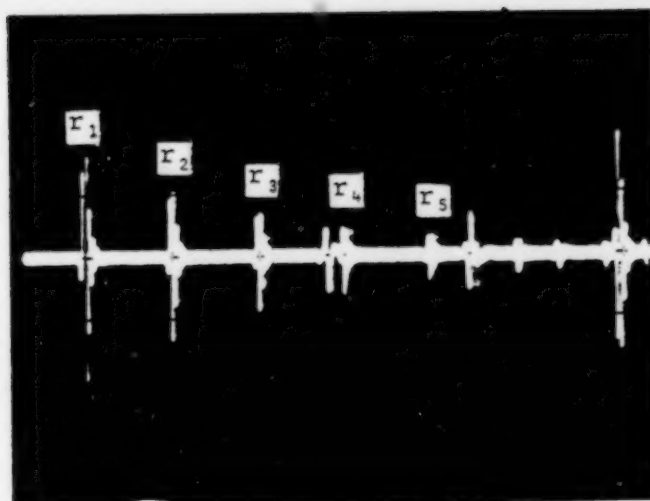
Scale: 1 μ s/cm

Figure 2-3. Ultrasonic pulses received with test system in pitch-catch mode.



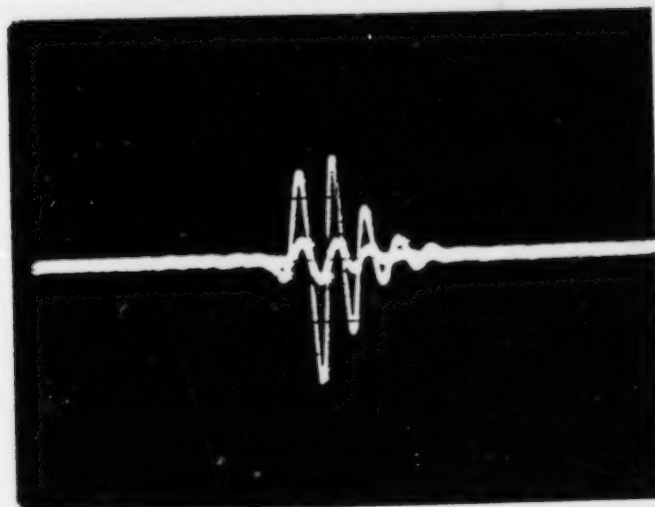
Scale: 100ns/cm

Figure 2-4. Superimposition of received pulses
p₁ and p₅.



Scale: 1ns/cm

Figure 2-5. Ultrasonic pulses received with test system in pulse-echo mode.



Scale: 100 μ s/cm

Figure 2-6. Superimposition of received pulses r_1 and r_5 .

4
3
2
1
0

As indicated above, the experimental measurements made were of inter-pulse time delays, which correspond directly to pulse transit times through the biofouling test material. For the purposes of this investigation, determination of the relative sound speed in the biofouling material with respect to water is of primary concern. This relationship was measured by repeating the pulse time delay measurements using the same test fixture filled with water. The sound speed ratio is the inverse of the ratio of the pulse delay times. Measurements with biofouling material and water in the test fixture were made under the same conditions. Results of these measurements are given in the following section.

2.3 SUMMARY OF RESULTS

Three test fixtures were used to measure the relative sound speeds in three samples of biofouling material. The first sample was a water/biomass mixture (approximately 50 percent free water) grown in a tank. The second was de-watered biomass similar to the first sample except that most of the water was removed by filtering. The third sample was cultured bacteria grown in a petri dish.

Each sample was tested in a different test fixture. Although the fixtures were all nominally of the same dimensions, they were not identical, and the slight differences caused easily measurable differences in the pulse transit times. Consequently, the transit times between different test fixtures are not directly comparable. However, the relative transit time of each sample in a given test fixture with respect to water in that same test fixture is a valid comparison of the samples. Each fixture was filled with water and tested to obtain the reference for each sample.

The test results are summarized in Table 2-1. This table shows the measured delay times (Δt) between the first and fifth received pulses for each of the three samples and for water in the test fixtures. The temperatures at which the measurements were made are also recorded because sound speed in water is sensitive to temperature. The uncompensated time delay

TABLE 2-1. SOUND SPEED MEASUREMENT RESULTS

Sample	At Sample μ sec	At Water* μ sec	At Ratio Sample/Water**	Sound Speed Ratio Sample/Water**	Temperature Correction for Sound Speed Ratio	Temperature Corrected Sound Speed Ratio
Water and Biomass	5.55 @ 24.5°C	5.54 25.5°C	1.002	.998	.0016	.999
De-Watered Biomass	5.66 @ 23.5°C	5.65 @ 24.5°C	1.002	.998	.0016	.999
Cultured Bacteria	5.56 @ 25.0°C	5.70 @ 24.7°C	1.0475	1.025	-.0005	1.024

*At is the measured time delay between the first and fifth pulse.

Three different test fixtures were used to test the three biofouling samples. Each water At value is for the test fixture used with the sample in the same row of the table.

**No temperature correction factor applied.

ratios and sound speed ratios are computed first. A temperature correction for the sound speed ratio is then computed on the basis of 0.0016 per °C temperature difference between the water and biofouling samples. This correction factor is derived from the sonic velocity correction factor for water at room temperature of 2.4m /sec-°C divided by the sonic velocity of 1500m /sec. Since the temperature of the water and biofouling samples were very close during the testing, this temperature correction factor had little effect on the sound speed ratio as shown in the last column.

The computed results are that the sound speeds in the first two samples are 99.98 percent of the sound speed in water. Since the experimental accuracy is no better than 0.02 percent, one may conclude that the sound speed in these two samples is indistinguishable from the speed of sound in water. However, the third sample consisting of cultured bacteria had a sound speed 2.4 percent greater than the sound speed in water. Since this is much larger than experimental uncertainty, the measured sound speed difference is significant. Nevertheless, since only three samples were tested, and since it is uncertain which of the three samples tested is most typical of actual biofouling material, there is some question whether the difference in sound speed between actual biofouling material and water in an operating condenser would be significant. This would have to be resolved by further experimentation.

2.3.1 Acoustic Impedance of Biofouling Material

The acoustic impedance of the biofouling material is the product of its sound speed and density. Similarly, the relative acoustic impedance of the biofouling material with respect to water is the product of the relative sound speed and relative density. It is this relative acoustic impedance which is important because it determines the detectability of the biofouling layer in contact with water by ultrasonic inspection techniques.

The relative sound speed of the biofouling material was measured to be in the range of 1.0 to 1.024, depending upon the sample composition and preparation. The density was measured using a picnometer to be in the range of 1.0 for water/biomass to 1.04 for dewatered biomass. There was not a sufficient quantity of cultured bacteria for a density determination. The

relative acoustic impedance of the material is the product of the relative density (specific gravity) and relative sound speed.

The relative acoustic impedances determined for each sample are presented in Table 2-2.

TABLE 2-2. RELATIVE ACOUSTIC IMPEDANCE OF BIOFOULING MATERIALS

Sample	Specific Gravity	Relative Sound Speed	Relative Acoustic Impedance
Water/Biomass	1.00	0.999	1.00
Dewatered Biomass	1.04	0.999	1.04
Cultured Bacteria	1.00*	1.024	1.02

*Assumed to be the same as water.

The results compare favorably with those of Loeb and Jarzynski¹ who determined an acoustic impedance of biomass relative to sea water of 1.03. However, since only three samples were tested, it is uncertain which sample is most typical of actual biofouling material, as indicated in the earlier discussion of sound speed measurement.

REFERENCES

1. Loeb, G., and J. Jarzynski. "Ultrasonic Detection of Microbial Slime Films." Proceedings, 6th OTEC Conference, DOE, Washington, D.C. 20585, 1979.

SECTION 3

DETECTION OF BIOFOULING BY ULTRASONIC TECHNIQUES

Ultrasonic techniques under consideration for the detection of biofouling on the inside of a water-filled metal tube depend upon the biofouling material having a different acoustic impedance than water. The interface between the biofouling material and the water must present a distinct change in impedance to the acoustic signal to make this interface reflective.

A pulse-echo technique for detection of biofouling is shown in Figure 3-1. A short pulse is transmitted by a transducer into the metal pipe wall. If biofouling is present, as shown in the figure, the pulse is reflected by the pipe/biofouling interface (r_1) and by the biofouling/water interface (r_2). The biofouling is detected and its thickness measured by observing the reflections of the pulse from the pipe wall/water interface.

The feasibility of detecting biofilms by this technique is determined by the strengths of the r_1 and r_2 reflections and the time delay between them. The strengths of the reflections are calculated by first calculating the power reflection and transmission coefficients at the interfaces using Equations 2-1 and 2-2. An example is presented below using the dewatered biomass from Table 2-2 and the properties of a stainless steel pipe (tubing).

$$\begin{aligned} a_{r_{pb}} &= \left[\frac{1.04 \times 1.5 \times 10^5 - 4.7 \times 10^5}{1.04 \times 1.5 \times 10^5 + 4.7 \times 10^5} \right]^2 = .88 \\ a_{r_{bw}} &= \left[\frac{1.5 \times 10^5 - 1.04 \times 1.5 \times 10^5}{1.5 \times 10^5 + 1.04 \times 1.5 \times 10^5} \right]^2 = 3.8 \times 10^{-4} \\ a_{t_{pb}} &= 1 - a_{r_{pb}} = 0.12 \\ a_{t_{bw}} &= 1 - a_{r_{bw}} = 0.9996 \end{aligned}$$

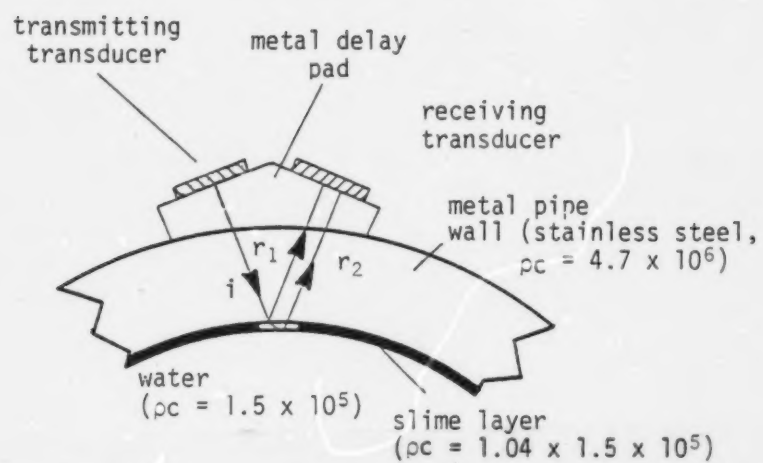


Figure 3-1. Detection of biofouling by reflection from slime layer interfaces (pulse-echo method).

In this notation, the subscripts are p for pipe, b for biofouling layer, and w for water. For example, $\alpha_{r_{pb}}$ is the power reflection coefficient for the pipe/biofouling layer interface. The relative acoustic impedance of the biofouling with respect to water is assumed to be 1.04 in these calculations. These coefficients indicate that at the pipe/biofouling interface, 88 percent of the pulse energy is reflected and 12 percent is transmitted across the interface. At the biofouling/water interface, only 0.04 percent of the energy is reflected.

By tracing the paths of the r_1 and r_2 reflected signals in Figure 3-1, one can calculate the received signal levels. Assuming the incident signal (the signal designated i in Figure 3-1) has a unity signal level in the metal pipe wall, the r_1 and r_2 signal levels are:

$$S_{r_1} = 0.88$$

$$S_{r_2} = 0.12 (0.0004) (0.12) = 5.5 \times 10^{-6}$$

The S_{r_1}/S_{r_2} power ratio is 1.6×10^5 or 52 dB, where dB = 10 log (power ratio).

The times of arrival at the receiving transducer of signals r_1 and r_2 differ by the flight time of r_2 through the biofouling layer. The time difference is:

$$\tau = \frac{2T}{(1.04)(1.5 \times 10^5)}$$

where T is the thickness of the slime layer in centimeters. For example, if $T = .005$ cm (50 μ m), which is the biofilm thickness above which condenser heat transfer is impeded, then $\tau = 64$ ns.

SECTION 4

CONCLUSIONS

Although additional experimentation is required, it appears that ultrasonic detection of biofouling materials on condenser tubes might be feasible, based on laboratory evaluations performed for this study. The processing of ultrasonic signals in the frequency and dynamic ranges required are within the capability of current technology. However, hardware has not been specifically developed to meet all the requirements of the biofouling application. A program to develop an acoustic system specifically designed for biofouling detection would be of value. This development program could emphasize the use of "off-the-shelf" ultrasonic equipment, whenever possible, to augment the capability of the equipment used in the current program.

A program for continuing the development of an ultrasonic detection device could include the following tasks:

1. A survey of available manufactured hardware.
2. Hardware acquisition/modification/design as appropriate, and acoustic characterization of additional biofouling samples.
3. Laboratory testing in a simulated condenser environment.
4. Field testing in a utility condenser.

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APPENDIX A
TASK 1 SUMMARY REPORT:
LITERATURE REVIEW OF CURRENT
METHODS FOR DETECTING CONDENSER BIOFOULING

CONTENTS

<u>Section</u>	<u>Page</u>
A1. INTRODUCTION.	A-5
A1.1 TECHNICAL BACKGROUND	A-5
A1.2 APPROACH	A-7
A2. SUMMARY OF BIOFOULING DETECTION METHODS	A-9
A3. BASIS FOR COMPARISON OF BIOFOULING DETECTION METHODS.	A-13
A4. A DESCRIPTION OF BIOFOULING DETECTION METHODS	A-17
A4.1 ULTRASONICS.	A-18
A4.1.1 Description of the Method	A-18
A4.1.2 Current Development Status.	A-21
A4.1.3 Sensitivity	A-21
A4.1.4 Advantages and Disadvantages.	A-21
A4.2 CONDENSER WATERSIDE PRESSURE DROP.	A-22
A4.2.1 Description of Method	A-22
A4.2.2 Current Development Status.	A-23
A4.2.3 Sensitivity	A-23
A4.2.4 Advantages and Disadvantages.	A-25
A4.3 OVERALL HEAT TRANSFER EFFICIENCY	A-25
A4.3.1 Description of the Method	A-25
A4.3.2 Current Development Status.	A-26
A4.3.3 Sensitivity	A-28
A4.3.4 Advantages and Disadvantages.	A-28
A4.4 TURBINE BACKPRESSURE	A-29
A4.4.1 Description of the Method	A-29
A4.4.2 Current Development Status.	A-29

CONTENTS (continued)

<u>Section</u>	<u>Page</u>
A 4.4.3 Sensitivity.	A-29
A 4.4.4 Advantages and Disadvantages	A-30
A 4.5 THE CARNEGIE-MELLON UNIVERSITY DEVICE	A-30
A 4.5.1 Description of the Method.	A-31
A 4.5.2 Current Development Status	A-31
A 4.5.3 Sensitivity.	A-31
A 4.5.4 Advantages and Disadvantages	A-33
A 4.6 THE LOCKHEED MISSILE AND SPACE COMPANY DEVICE	A-33
A 4.6.1 Description of the Method.	A-34
A 4.6.2 Current Development Status	A-34
A 4.6.3 Sensitivity.	A-34
A 4.6.4 Advantages and Disadvantages	A-36
A 4.7 THE MONIREX FOULING DEVICE.	A-36
A 4.7.1 Description of the Method.	A-36
A 4.7.2 Current Development Status	A-37
A 4.7.3 Sensitivity.	A-37
A 4.7.4 Advantages and Disadvantages	A-37
A 4.8 THE TUBULAR SIDESTREAM REACTOR.	A-37
A 4.8.1 Description of the Method.	A-38
A 4.8.2 Current Development Status	A-38
A 4.8.3 Sensitivity.	A-38
A 4.8.4 Advantages and Disadvantages	A-39
A 4.9 THE ANNULAR SIDESTREAM REACTOR.	A-39
A 4.10 STANDARD PLATE COUNTS	A-40
A 4.10.1 Description of the Method.	A-40
A 4.10.2 Current Development Status	A-40
A 4.10.3 Sensitivity.	A-40
A 4.10.4 Advantages and Disadvantages	A-41

CONTENTS (continued)

<u>Section</u>	<u>Page</u>
A4.11 MONITORING STREAM COMPOSITION.	A-41
A4.11.1 Description of the Method	A-41
A4.11.2 Current Development Status.	A-41
A4.11.3 Sensitivity	A-41
A4.11.4 Advantages and Disadvantages.	A-42
APPENDIX A REFERENCES	A-43
APPENDIX A BIBLIOGRAPHY	A-45

SECTION A1

INTRODUCTION

A1.1 TECHNICAL BACKGROUND

The accumulation of biofouling materials results in accelerated corrosion of metal surfaces and/or impairs heat transfer from the condensing stream to the cooling water flowing through the condenser tubes. The loss of heat transfer efficiency is brought about by two mechanisms:

1. Biofouling has a lower thermal conductivity than water; therefore, biological accumulation increases the resistance to the transfer of heat through the condenser tube, thereby reducing the condenser heat transfer efficiency.
2. Deposits increase frictional resistance to cooling water flow thus reducing flow rate for a given pressure drop (or, alternatively greater pumping power is needed to maintain the same flow rate or flow velocity). This reduced flow rate limits the heat energy that can be removed by the cooling water.

The inability to remove heat from the condensing stream results in higher condensing steam temperature and a corresponding higher turbine backpressure. Higher turbine backpressure limits the expansion of steam through the turbine and directly results in a loss of generation capacity.

Cooling water systems, especially in the heat transfer tubes and inlet, outlet, and turning heads of the condenser, provide microbial organisms with a warm, oxygenated, nutrient-rich environment in which to grow. When this growth is uncontrolled, severe coating and eventual plugging of the tubes occurs, resulting in a reduction of heat transfer. If this situation persists, a generating unit

may have to reduce load or be shutdown to clean the condenser. In either case, this results in a costly reduction in generating unit availability and reliability.

To protect the condenser from biofouling, a number of methods are commonly used to either retard biological growth or mechanically remove it before it reaches a critical condition. Mechanical cleaning methods include permanently installed systems, such as the American MAN System, and in-stream methods, such as Amertap's abrasive ball method. These mechanical cleaning methods have been used at a number of plants and have met with some success. The vast majority of plants use a method involving the addition of chlorine into the condenser cooling water inlet to control biofouling. High concentrations of residual chlorine are toxic to biofouling and other aquatic organisms. When the proper doses of total residual chlorine are used, biofouling can usually be controlled within tolerable limits.

In order to protect other aquatic life, the EPA has limited the chlorination period and the chlorine concentrations in the discharge from an individual generating unit. Regulations allow a free residual chlorine concentration of 0.1 mg/L (average) and a maximum instantaneous concentration of 0.5 mg/L for one two-hour period per day. Proposed New Source Performance Standards require zero discharge of total residual chlorine except where it is demonstrated that biofouling cannot be controlled under these conditions. In these cases, a maximum total residual chlorine concentration of 0.14 mg/L is allowed and limited to two hours per day per discharge point.³ These regulations emphasize the need to "minimize" the use of chlorine by close control of chlorine additions and enhancement of the effectiveness of each application.

In addition to an accurate chlorine metering system, two critical measurements are needed to properly control biofouling at these reduced chlorine concentrations. The first is accurate measurement of residual chlorine, both at the point of addition and at the condenser outlet, and the second is accurate measurement of condenser performance relative to the

chlorine dosage and biofouling. While some problems still exist with the long term reliability of continuous chlorine analyzers, accurate measurement of condenser performance is a more significant problem.

Determination of condenser performance is a complex calculation requiring the input of data from both the water and steam sides of the condenser. This calculation can be modified to allow the calculation of an overall heat transfer coefficient and its component resistances to heat flow such as the fouling factor. Many plants today automatically monitor and calculate fouling factor continuously with process computers. However, the accuracy of this method is highly dependent upon the reliability and sensitivity of the monitoring instruments and upon plant maintenance practices. Changes in load or steam flow rate, cooling water and ambient temperatures, and many other factors cause variation in the calculated fouling factor. This variation makes fouling factor data difficult to interpret and masks many of the subtle changes that occur during the initial stages of the biofouling process.

More direct and simpler approaches to monitoring of fouling are now being developed. More accurate and reliable means of detection would result in improved generating unit availability. These detection methods would also become an integral part of a biofouling control program. These methods could greatly enhance the effectiveness of low-level chlorination as well as aid in meeting discharge regulations.

A1.2 APPROACH

The Task 1 effort was directed at searching literature to determine the current methods used to determine biofouling and to identify potential methods that appear promising based on research results. The relative merits, extensiveness of application, and practicality of these methods will be evaluated and compared in subsequent sections of this summary.

The literature search was conducted using on-line abstracts from the Lockheed Retrieval Service. In addition to this abstract service, both Radian and the University of Texas library facilities were utilized. The approach to Task 1 involved identifying the various methods of biofouling detection both currently in use and under consideration. This information was summarized by detection method, comparison criteria were developed, and all methods were compared. The results of each of these activities are reported in the remainder of this appendix.

SECTION A2

SUMMARY OF BIOFOULING DETECTION METHODS

This section summarizes the current and potential methods of biofouling detection. These methods are shown in Table A2-1 along with information concerning the development status and sensitivity of each method for detection of biofouling. Of the methods presented, condenser cooling water pressure drop, turbine backpressure monitoring, and overall heat transfer efficiency are the most common methods currently being used for detecting condenser tube fouling. However, the complexity of the factors involved in their computation or measurement result in very low sensitivity to the early growth phase of biofilm development. These methods are indicators of only severe fouling accumulations and are therefore, of limited value to a chlorine minimization program.³

Three detection methods found in the literature survey that are potentially applicable to the detection of biofouling include:

1. The Monirex Fouling Device⁴ - This device is used to detect nonbiological fouling of petroleum fractions in various refining processes by a heat transfer measurement. However, there is little similarity between the petroleum fouling materials and condenser biofouling encountered in the steam electric utility industry. Therefore, the application of this technique to biofouling would require additional development and sensitivity would be limited as in other heat transfer techniques.
2. Standard Plate Counts - These are effectively used to determine the presence of biofouling organisms. Standard plate counts are made from bacterial colonies that grow on a media that has been exposed to the cooling water. The development of a number of these colonies under the accelerated growth conditions of the media indicate the presence of biofouling organisms. Development of bacterial colonies

TABLE A2-1. SUMMARY OF BIOFOULING DETECTION METHODS

Detection Method	Developmental Status of Method for Biofouling Detection	Sensitivity to Biological Growth Phase	Accuracy	Comments
Ultrasonics	R&D	I, E	+1% @ 50 μm (Ref. 7)	Direct measurement
Condenser Pressure Drop	Commercial	E, P	N/A	Common indirect detection method
Tubular Reactor	R&D	N/A	N/A	Sidestream simulator
Annular Reactor	R&D	N/A	N/A	Sidestream simulator
Heat Transfer Resistance Methods				
Overall Heat Transfer Efficiency	Commercial	E, P	+4% (Ref. 6)	Common indirect detection method
Turbine Backpressure	Commercial	E, P	N/A	Most common indirect detection method
Carnegie-Mellon University Device	R&D	E*	+10% (Ref. 5) +12% (Ref. 6)	Developed for Ocean Thermal Energy Conversion biofouling applications
Lockheed Missile and Space Company Device	R&D	E*	3×10^{-5} (hr-°F-ft ²)/Btu (Ref. 6)	Developed for Ocean Thermal Energy Conversion biofouling detection
Monirex Fouling Device	Potential	E, P	N/A	Developed for petroleum process fouling detection
Standard Plate Counts	Potential	N/A	N/A	Commonly used in evaluating biofouling control agent effectiveness; used for detection in cooling tower systems
Chemical/Biological Monitoring	Potential	N/A	N/A	Commonly used in evaluating biofouling control agent effectiveness

I - Induction phase or primary biofilm formation (biofilm thickness 0 to 40-50 μm).

E - Exponential accumulation phase (biofilm thickness greater than 35-45 μm).

P - Plateau or steady-state phase.

N/A - Data not available.

* - Overlap of Induction and Exponential phases may allow these methods to detect growth during Induction phase.

would be difficult to correlate with biofouling accumulations in condenser tubes. For this reason, the usefulness of this method is limited to supporting other detection/measurement techniques.

3. Chemical/Biological Monitoring Techniques - These techniques utilize total organic carbon (TOC) and adenosine triphosphate (ATP) as indicators of biological growth. ATP is only found in living cells and is released to the cooling water rapidly upon death. Monitoring of ATP and TOC at the condenser cooling water inlet and outlet provides a means of estimating biomass accumulation in the condenser. The specialized analytical equipment required to monitor these parameters and the batch nature of the analysis make this method of biofouling detection impractical at this point in the development.

The new methods currently under active development are sidestream reactors, heat transfer resistance methods, and ultrasonics. The sidestream reactors consist of tubular and annular reactors. These reactors attempt to simulate heat exchanger conditions and are limited by their ability to duplicate these conditions. These techniques are in the early developmental stage and require supplemental microscopic and manual biomass accumulation analysis to determine biofouling accumulation thickness.

Heat transfer resistance methods have been developed for detection of biofouling of heat exchangers in Ocean Thermal Energy Conversion (OTEC) systems. The Carnegie-Mellon University (CMU)⁵ and Lockheed Missiles and Space Company (LMSC)⁶ devices have been the subject of several laboratory and field tests. In their current state of development, these devices require highly skilled technicians to operate and interpret measurements. These devices are also sidestream simulators, and their usefulness is limited by their ability to duplicate condenser operating conditions. The sensitivity of these devices to the early growth phase of biofilm development is not well defined, but appears to be effective in measuring thickness in the 35-50 μm range.³

Ultrasonics is currently the only technique for direct measurement of biofouling film thickness under consideration. Its application to thickness measurement of materials is used extensively. Its high accuracy in metal thickness measurement in the 50 μm range⁷ closely correlates to the 35-50 μm detection range of other biofouling detection methods. Preliminary studies of the acoustic properties of biofouling materials indicate that detection of biofilms less than 50 μm in thickness may be feasible. This capacity and the type of equipment required to perform these measurements is yet to be determined and will be dealt with in detail in Task 2. The practicality of this approach will be determined by the extensiveness and complexity of equipment required and the difficulty in interpreting measurements.

Of the methods found in this literature search, the CMU and LMSC heat transfer resistance devices and ultrasonics are the methods that appear to have the highest potential for commercial development. These techniques may assume a key role in the implementation of effective biofouling control and chlorine minimization programs. The basis for comparison of these methods is discussed in Section A3.

SECTION A3

BASIS FOR COMPARISON OF BIOFOULING DETECTION METHODS

In this section, some of the more important criteria for comparing biofouling detection methods are discussed. Because of the variety of methods used to detect biofouling and the relatively limited data available concerning their use, comparing these methods on a quantitative basis is difficult. Evaluation criteria outlined initially included development status, extensiveness of application, practicality of approach, and sensitivity. The literature survey indicates that most applicable methods are in the developmental stages with limited testing background; thereby, the value of the first two evaluation criteria in this analysis is reduced. The practicality of the detection methods is difficult to determine and must be estimated on the basis of limited discussions of techniques and equipment used to detect biofouling. The sensitivity of the detection methods to the various thicknesses of the biofilm is the most important comparison criteria. Therefore, the sensitivity will be discussed in some detail in order to properly define the term for this evaluation. Task 2 will address the numerical significance of the sensitivity. This evaluation will deal primarily with the qualitative significance of biofouling detection sensitivity.

The development or growth of biofouling film has been found to proceed in a sigmoidal manner with three distinctive phases:

1. Induction or primary biofilm formation.
2. Exponential accumulation or logarithmic growth phase.
3. Steady-state or plateau phase.

Figure A3-1 from Bryers and Characklis⁸ shows the relationship of these growth phases (biofilm thickness) to the increase of heat transfer and frictional resistances in a condenser. The induction phase occurs during the period from clean surface conditions to the onset of frictional resistance increase. During this phase, bacterial attachment proceeds in a two-stage process:

1. Reversible adhesion where bacteria are loosely attached and are removed by mild rinsing, and
2. Irreversible attachment which occurs after several hours of exposure to the tube surface. (This stage involves the secretion of gelatinous substances that entrap suspended matter and other biological growth in a complex matrix. Removal of biofouling materials at this point requires severe physical methods.

In turbulent flow, there is a laminar sublayer of fluid along the tube wall. In this layer the fluid flows smoothly in layered (laminar) type flow. Experimental measurements indicate that the maximum thickness of biofilm accumulation below which no effect is observed on the system frictional resistance (waterside pressure drop) is between 35 and 40 μm .⁹ This thickness corresponds to the viscous sublayer. The biofilm can develop from a clean surface to this thickness in about 37 hours.

The logarithmic growth phase refers to the period of time during which the biofilm accumulation increases exponentially, resulting in similar increases in heat transfer and frictional resistances. This phase may overlap with the latter stage of the induction growth phase.

The plateau phase or steady-state phase is the period during which deceleration of the accumulation rate occurs and pseudo-steady-state thickness is maintained. Biofouling accumulations are not of uniform thickness and are subject to peeling and sloughing.

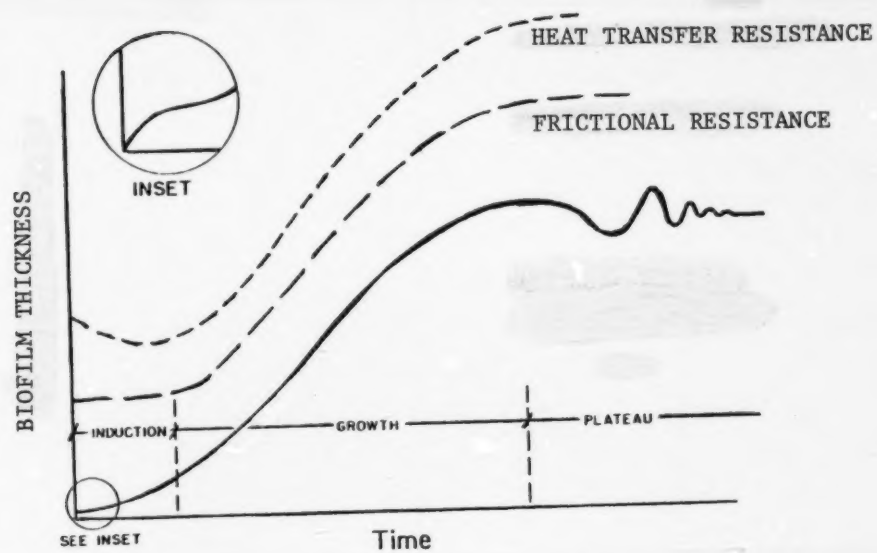


Figure A3-1. Phases of biofilm development.⁴

The previous discussion indicates that a biofouling control program must concentrate on preventing accumulation above the viscous sublayer. Furthermore, the program should concentrate on the removal of biofouling materials in the early part of the induction phase before microorganisms irreversibly attach to the condenser tube surface. Experiments indicate that 10- μ m accumulations can occur in 8-to 10-hour time periods.⁸ It is on the thin biofilms that chlorine and other oxidants are most effective and most efficiently used (i.e., their use is minimized). If biofilms are allowed to accumulate, the effectiveness of chemical oxidants and biocides, applied at low dosage, is greatly reduced due to poor penetration of biofouling materials.

In order to minimize the oxidant and biocide concentrations required to control biofouling, a reliable means of detection of biofilms in the 10- μ m thickness range is required. The restricted chlorine residuals currently allowed can only be effective at industrial installations if chlorine use is coordinated with biofilm growth dynamics. For this reason, the sensitivity of the detection method is the most important evaluation criteria.

The sensitivity range mentioned above served as the basis for selection of the CMU and LMSC heat transfer resistance and ultrasonic detection as the methods having the highest probability for commercial development for biofouling applications.

SECTION A4

A DESCRIPTION OF BIOFOULING DETECTION METHODS

This section describes the methods found in this literature search for detecting biofouling in condenser tubes. Included for each method is a brief description of the method, the current status of development, and the method's sensitivity in detecting biological film growth. Also included is a short summary of the advantages and disadvantages associated with each method. It should be noted that literature on all detection methods is extremely limited and, where appropriate, advantages/disadvantages reflect engineering judgment and implications from the literature. A comparative evaluation of the methods described in this section is presented in Section A2.

The literature search performed for Task 1 revealed the following proposed or applied methods for biofouling detection:

1. Ultrasonics.
2. Monitoring increases in condenser waterside pressure drop.
3. Monitoring overall heat transfer efficiency.
4. Monitoring increases in turbine backpressure.
5. The Carnegie-Mellon University (CMU) device, a simulator using heat transfer resistance.
6. The Lockheed Missile and Space Company (LMSC) device, a simulator using heat transfer resistance.
7. The Monirex fouling device, a simulator using heat transfer resistance.
8. Sidestream simulation of a condenser using a tubular reactor to monitor increases in fraction and heat transfer resistance.

9. Sidestream simulation of a condenser using an annular reactor, to monitor increases in shear and heat transfer resistance.
10. Standard plate counts.
11. Monitoring the chemical or biological content of the inlet and/or outlet water.

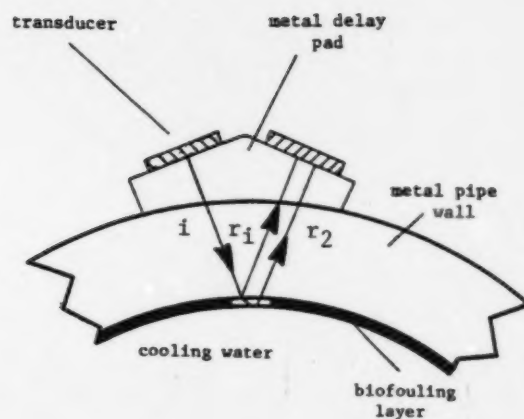
A4.1 ULTRASONICS

Ultrasonics refers to the use of transmitted high frequency sound waves. These ultrasonic waves are reflected at the interfaces between materials of different acoustic properties. It is this characteristic of the material that would be used in the application of this method to detect biofouling in a condenser tube.

A4.1.1 Description of the Method

Two methods employing ultrasonic waves are commonly used to measure the thickness of a layer of material. These are the pulse-echo method and the resonance method. Figure A4-1 shows the principle behind the pulse-echo method. A short burst of sonic energy is transmitted by a transducer probe into the tube wall. The time required for ultrasonic waves to traverse the tube and reflect from the tube wall/biofilm interface and reflect from the biofilm/water interface and return to a sensor are measured. From these measurements, the thickness of the biofouling layer can be calculated.

The resonance method uses the properties of standing waves to determine the thickness of the biofouling layer. Figure A4-2 illustrates this method of measurement. The frequency of the ultrasonic waves is adjusted to correspond to a resonant frequency of the tube. Biofouling accumulation will change the resonance frequency of the tube. When a number of resonant frequencies have been determined, mathematic relationships between the series of resonant frequencies and the thickness of the biofilm can be developed.



- i - ultrasonic energy pulse
- r_1 - reflection from metal/biofouling layer interface
- r_2 - reflection from biofouling layer/water interface

Figure A4-1. Detection of layer thickness by direct reflection from biofouling layer interfaces - pulse-echo method (from Loeb and Jarzynski¹⁰).

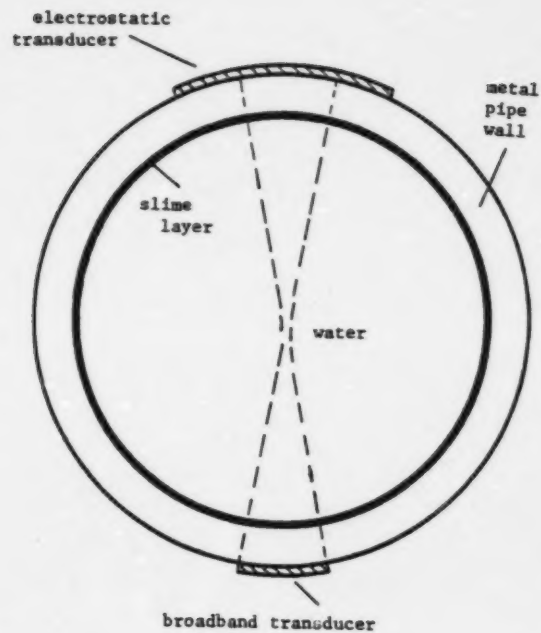


Figure A4-2. Detection of layer by measuring the resonance frequency of the metal tube - resonance method (from Loeb and Jarzynski¹⁰).

A4.1.2 Current Development Status

Only one investigation into the use of ultrasonics to detect biofouling was found by this literature search.¹⁰ Therefore, it can be concluded that a significant amount of research and testing is needed before this method can be considered a viable method for detecting biofouling in condenser tubes. The investigation was performed under the Department of Energy's Ocean Thermal Energy Conversion program on biofouling from a condenser using seawater. No information was found pertaining to the use or study of ultrasonics in fresh water condenser tubes.

A4.1.3 Sensitivity

Due to the lack of research into the application of this method for biofilm detection, the sensitivity of ultrasonics for this application is unclear. Loeb and Jarzynski¹⁰ report that biofouling layers of less than 10 μm in thickness may be detectable with this method. Whether reliable data can be obtained in a commercial condenser or a condenser simulator at these thicknesses is unknown. The investigation in Task 2 of ultrasonic sensitivity in similar applications may indicate the potential minimum thickness which can be reliably measured using current ultrasonic technology.

A4.1.4 Advantages and Disadvantages

Advantages using ultrasonics to detect biofouling include:

1. Potentially high sensitivity-permitting detection of induction phase growth.
2. Accuracy - in other applications, ultrasonics have been shown to be of superior accuracy compared to other nondestructive testing methods.⁷
3. Only one surface needs to be accessible.

4. Electronic operation allows automatic, rapid scanning, monitoring, and process control-permanent records can be made.
5. Would not interfere with the operation of the condenser or other equipment in the vicinity.

Disadvantages in using ultrasonics to detect biofouling include:

1. The method has not been proven, therefore it is not currently available on a commercial basis.
2. Highly skilled operators are required.
3. Development of measurement procedures and correlation for biofouling applications require highly specialized technical knowledge.
4. Irregular or rough shapes are difficult to measure (good contact between transducer and the tube is essential).
5. Reference standards are needed.
6. The presence of any coatings must be taken into account.

A4.2 CONDENSER WATERSIDE PRESSURE DROP

The pressure drop across the waterside of the condenser can be used to detect biofouling. As the biofilm grows in thickness, resistance to fluid flow through the tube will increase resulting in an increase in pressure drop across the condenser.

A4.2.1 Description of the Method

As the biological film grows in thickness, the amount of pressure required to push a given amount of fluid through the condenser tube increases. By monitoring the pressure drop across the waterside of the condenser, biofouling can be detected.

Figure A4-3 shows the relationship between biofilm thickness and frictional resistance to fluid flow. As this figure illustrates, at thicknesses above approximately 40 μm , the frictional resistance increases with biological accumulation. Below 40 μm , no increase in frictional resistance was observed.

Bryers et al.⁹ have shown that a biofilm will not increase the resistance to fluid flow within a tube until portions of the biofilm protrude through the viscous sublayer into the turbulent regime.

As Figure A4-3 shows, there is a relationship between biofilm thickness and frictional resistance to flow above the viscous sublayer. The increased frictional resistance can be monitored by measuring the condenser waterside pressure drop and correlated to biofilm thickness or heat transfer resistance.

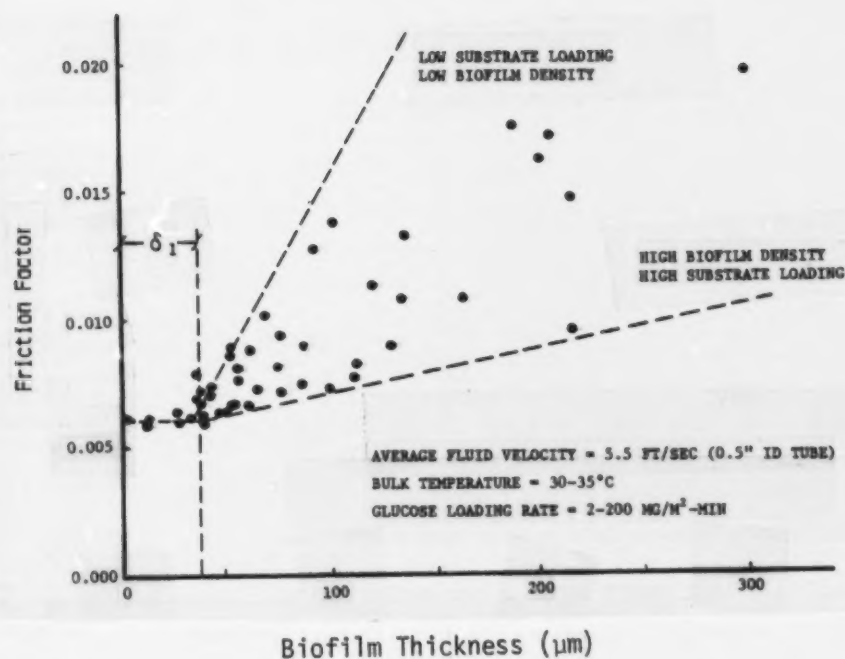
A4.2.2 Current Development Status

Monitoring condenser waterside pressure drop to detect biofouling is a common practice in many power plants. No information was discovered during this literature search which indicated that any research was conducted or is proposed to increase the sensitivity or reliability of this method.

A4.2.3 Sensitivity

Detection of biofouling using the condenser waterside pressure drop is limited to biofilm growth whose thickness exceeds the viscous sublayer. The sublayer is generally in the range of 40-50 μm .

In actual practice this sensitivity is difficult to achieve. Variations in operation, such as pump wear and difficulty in isolating biofouling as the sole cause for increased condenser waterside pressure drop, limit the reliability and detection sensitivity of this method.¹¹



δ_1 - indicates the thickness of the viscous sublayer

Friction factor is a dimensionless number that is a correlation between tube wall or biofilm roughness and Reynolds' number.

Figure 4-3. The effect of biofilm thickness on friction factor in a circular tube (from Bryers et al.).⁹

A4.2.4 Advantages and Disadvantages

The primary advantages for monitoring the condenser waterside pressure drop to detect biofouling are:

1. Data can be collected as a normal part of the plant's operational records.
2. Measurements are easily performed.
3. The required instrumentation is available and well demonstrated.
4. Condenser waterside pressure drop is independent of turbine/steam cycle operation.

Some of the main disadvantages to using this method are:

1. It can be difficult to segregate the contribution of biofilm development to increasing fluid flow resistance from other factors.
2. Accuracy is limited to that of the correlation developed to relate biofouling to the condenser waterside pressure drop.
3. It is dependent on circulating water pump performance.
4. Accurate measurement of flow rates in large diameter pipes can be difficult.

A4.3 OVERALL HEAT TRANSFER EFFICIENCY

Attachment of microorganisms to the condenser tube wall results in an increase in the resistance to radial heat transfer through the tube wall. This increase in heat transfer resistance can be used to detect biofouling.

A4.3.1 Description of the Method

The overall heat transfer efficiency of a condenser can be determined by measuring the temperature of the inlet and discharge water streams, or the quality (fraction in vapor phase) and temperature (and pressure if superheated) of the steam, and the rate of

condensation.¹² Careful monitoring of the heat transfer efficiency versus time curve should allow detection of biological film growth.

Biological film growth can decrease the heat transfer efficiency in two ways. Heat transfer efficiency can be decreased due to the lower thermal conductance of the biofilm compared with the thermal conductance of the water (conductive resistance) and can also decrease due to increased frictional resistance of the biofilm protruding through the viscous sublayer into the turbulent flow regime (convective resistance). Figure A4-4 shows experimental measurements for these types of resistance with biofilm growth.

As Figure A4-4 indicates, in the early stages of growth and before the film protrudes through the viscous sublayer (induction phase growth), the measured overall resistance actually decreases slightly, whereas at thicknesses greater than the viscous sublayer, the resistance increases. Characklis et al.¹ have determined that the thermal conductivity of induction phase fresh water biofilm is not significantly different from that of the water. Thus, detectable increases in heat resistance are probably due to convective resistances generated by increased frictional resistance. Figure A4-4 shows that in the early stages the primary heat transfer resistance is convective.

A4.3.2 Current Development Status

Monitoring the overall heat transfer efficiency of condensers is a demonstrated technology used in some power plants for detecting biofouling. No information was discovered during this literature search which indicated that any research was conducted or is proposed to increase the sensitivity or reliability of this method.

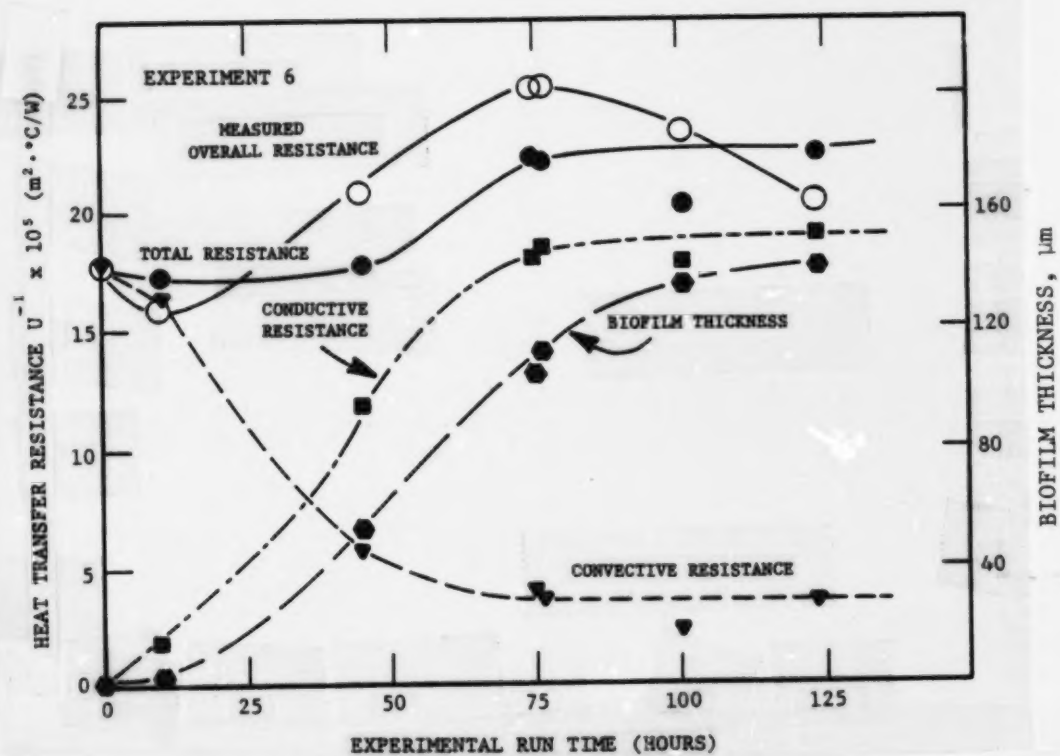


Figure A4-4. Heat transfer resistance changes with time as a result of biofilm development (from Characklis et al.).¹

A4.3.3 Sensitivity

A measurable increase in the heat transfer resistance due to biofouling does not occur until the biofilm thickness exceeds the viscous sublayer. This layer is generally in the range of 40-50 μm . Thus, the sensitivity of methods monitoring heat transfer resistance is theoretically limited to this range.

In actual practice, sensitivity in this range is difficult to achieve by monitoring the overall heat transfer efficiency. Many other factors, such as corrosion, cooling water inlet temperature, changes in cooling water flow rate or condensing steam rate, may also affect the overall heat transfer efficiency. These factors may either increase or decrease the heat transfer rate depending on when and in what combinations they occur.

A4.3.4 Advantages and Disadvantages

Some advantages to using this method are:

1. Data can be collected as a normal part of the plant's operational records.
2. Measurements can be easily performed.
3. Instrumentation is relatively simple.

Some of the disadvantages are:

1. The contribution of biofilm development to a decrease in overall heat transfer efficiency can be difficult to segregate from other factors.
2. Accuracy is limited to that of correlations developed to relate biofouling to condenser heat transfer efficiency.
3. Instrumentation must be calibrated on a regular basis to insure accuracy.

4. Interpretation of results is difficult because of the complexity of the data inputs and other process variables that can affect the calculation of the heat transfer efficiency.

A4.4 TURBINE BACKPRESSURE

The most widely used method of monitoring condenser fouling in the utility industry is the close surveillance of turbine backpressure.

A4.4.1 Description of the Method

Turbine backpressure is directly related to the condenser heat transfer efficiency. When biofouling reduces heat transfer, a slightly higher condensing temperature is encountered on the steam side of the condenser; resulting in a higher pressure (reduced vacuum) condition. The higher backpressure limits the steam condensation rate and flow through the turbine and results in a loss of generating capacity. This method involves the monitoring and recording of turbine backpressure readings. This can be performed using standard monitoring equipment supplied by the turbine and condenser manufacturer.

A4.4.2 Current Development Status

Monitoring turbine backpressure to detect biofouling is a common practice in many power plants. No information was discovered during this literature search which would indicate that any research was conducted or is proposed to increase the sensitivity or reliability of this method.

A4.4.3 Sensitivity

As discussed in Section A4.3.1, measurable heat transfer resistance due to biofouling does not occur until the film growth exceeds the viscous sublayer. This layer is generally 40-50 μm thick. Therefore, the theoretical sensitivity limits for detecting biofouling by monitoring turbine backpressure is in this range.

In actual practice this sensitivity is difficult to achieve. Variations in operation, turbine pressure, and other parameters, such as cooling water flow rate and other types of fouling, make it difficult to isolate and monitor the biofilm's contribution to changes in heat transfer resistance.

A4.4.4 Advantages and Disadvantages

The primary advantages for using the turbine backpressure monitoring method include:

1. Data can be collected as a normal part of the plant's operational records.
2. The method is currently in use.
3. Measurement is relatively easy to perform.
4. Instrumentation is available and well demonstrated.

There are disadvantages to using this method. Some of these are:

1. It can be difficult to segregate the contribution of biofilm development to increasing fluid flow resistance from other factors such as corrosion, silt deposition, operational fluctuations, etc.
2. Accuracy is limited to the accuracy of correlations developed to relate biofilm growth to the turbine backpressure.

4.5 THE CARNEGIE-MELLON UNIVERSITY DEVICE

Investigators at Carnegie-Mellon University (CMU) have developed a device to simulate condenser tube performance and monitor biofouling based upon changes in heat transfer resistance.⁵ The device has been used in extensive field test evaluations by the University of Hawaii, Tracor Marine, and the National Data Buoy Office. Literature concerning the use of this device is

very limited. Much of the subsequent evaluation of this method is based on judgments and implications derived from the literature.

A4.5.1 Description of the Method

The CMU device uses highly accurate temperature measurements to calculate heat transfer capabilities of simulated condenser tube conditions. Heat transfer efficiency is measured by heating the fluid flowing through the device to a steady-state temperature slightly greater than the process temperature, removing the heating source, and measuring the transient temperature change as the fluid stream cools. This cooling (temperature) versus time curve can then be used to calculate the heat transfer capabilities of the tube/fluid interface. Figure A4-5 presents a diagram of the CMU device.

A4.5.2 Current Development Status

The CMU device is a proposed OTEC detection method. Considerable research is being conducted to investigate its applicability in monitoring biofouling in OTEC condenser tubes. This device is currently being tested in some power plants to monitor biofouling.

A4.5.3 Sensitivity

The accuracy and reliability of the CMU device depends upon the instrument's ability to simulate actual condenser tube performance. Differences between the simulator and actual condenser may influence the rate of biological growth, affecting the test results.

Theoretically, the sensitivity of the CMU device is limited by the thickness of the viscous sublayer in the simulator. As discussed in Section A4.4.1, increases in heat transfer resistance due to biological film growth do not become detectable until the biofilm thickness exceeds the viscous sublayer

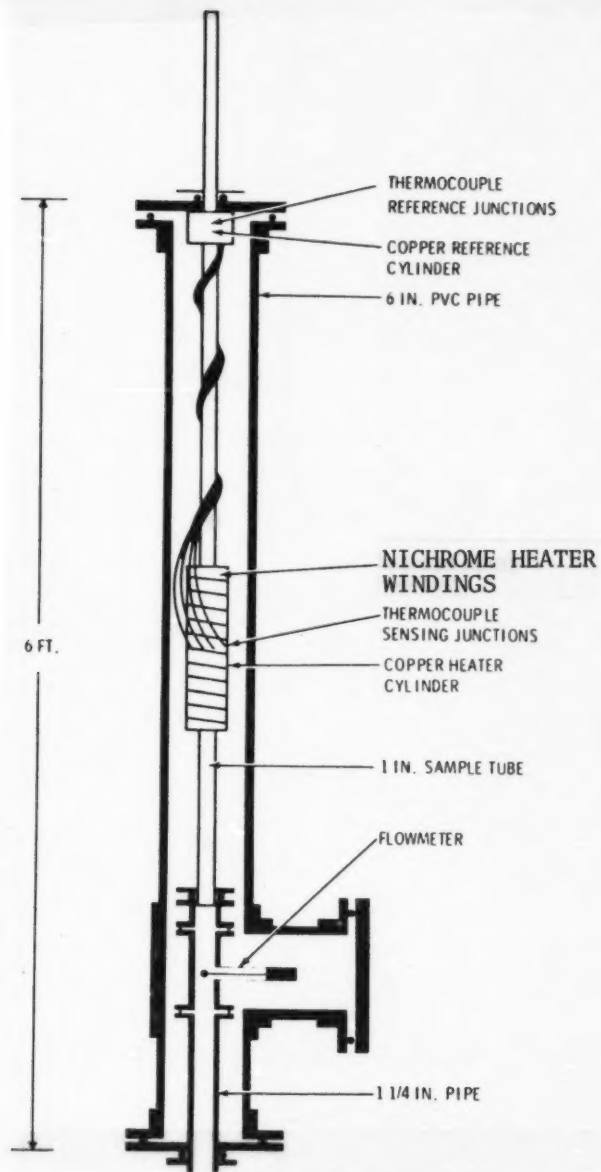


Figure A4-5. CMU biofouling measurement device (from Fetkovick⁵).

thickness. The ability of the CMU device to detect biofilms near this theoretical limit should be much better than that of the overall heat transfer efficiency, turbine backpressure, and condenser pressure drop methods. The use of a simulator should provide more accurate measurement of process conditions (such as pressure and fluid flow rate) and allow better control of other variables affecting heat transfer resistance.

A4.5.4 Advantages and Disadvantages

Some of the advantages of using the CMU device are:

1. The method has been demonstrated in five separate OTEC field tests.
2. The accuracy of this device can be excellent when condenser operating conditions are closely simulated.
3. The device can be very reliable in clear water applications.
4. Measurements are isolated from operational variations.

Some of the disadvantages of this device are:

1. Skilled operators are necessary.
2. The ability of the device to simulate different condenser operating conditions requires close monitoring and adjustment.
3. Other forms of fouling material, such as corrosion products, can interfere with testing by adhering to the heating element.

A4.6 THE LOCKHEED MISSILE AND SPACE COMPANY DEVICE

The Lockheed Missile and Space Company (LMSC) has developed a device to simulate and measure increases in heat transfer resistance in condenser tubes due to biological film growth. Literature dealing with the use of this device is very limited. Much of the subsequent evaluation of this method is based on judgment and implications derived from the literature.

A4.6.1 Description of the Method

The LMSC device is similar to the CMU device. The LMSC device simulates the conditions of the condenser tube in an instrument where accurate temperature measurements can be made. A heat transfer block, surrounding a simulated condenser tube, is designed to provide a known thermal resistance to heat flow. This results in a radial temperature gradient through the block. Temperature measurement in the block allows the heat transfer resistance of the system to be calculated. Changes in this resistance due to biofilm development at the tube wall/water interface can be measured by the increase in power required to maintain a constant temperature gradient. Figure A4-6 presents a diagram of the LMSC devices.

A4.6.2 Current Development Status

The LMSC device has not been studied as extensively as the CMU device. It is a proposed OTEC detection method and research is being conducted to investigate its ability to monitor biofouling in OTEC condenser tubes.

A4.6.3 Sensitivity

As with the CMU device, the accuracy and reliability of the LMSC device will depend, to a large extent, on the ability of the instrument to simulate actual condenser tube operation. The LMSC device monitors biofouling using heat transfer. Therefore, as discussed in Section A4.4.1, its theoretical sensitivity limit is related to the thickness of the viscous sublayer.

Owens⁶ gives a "subjective" comparison of the LMSC, CMU, and overall efficiency methods. This comparison lists the LMSC as the most accurate of the three, followed by the CMU device.

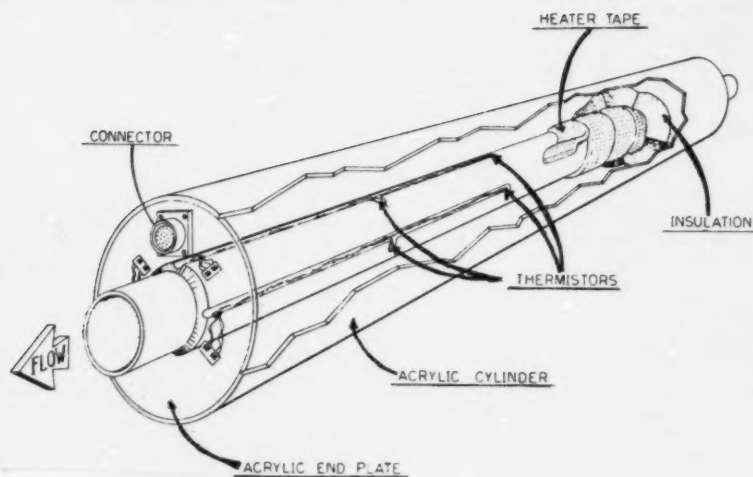


Figure A4-6. Conceptual diagram of LMSC heat transfer measuring test section (from Owens)⁶.

A4.6.4 Advantages and Disadvantages

Some advantages associated with using the LMSC method are:

1. This method can be very accurate.
2. Reliability should be good.
3. Measurements are isolated from operational variables.

Among the LMSC's disadvantages are:

1. Skilled operators are needed.
2. The ability of the device to simulate actual condenser operation must be verified by other testing methods.
3. Other forms of fouling material can interfere with determining biofouling.

A4.7 THE MONIREX FOULING DEVICE

UOP, Inc. has developed the Monirex Fouling test for detecting fouling in petroleum streams. This test may be applicable to condenser biofouling detection.

A4.7.1 Description of the Method

In the Monirex device, a preheated process stream contacts a hot metal wire in a test cell. The temperature of the wire is designed to model the condenser tube wall temperature. By regulating flow rate, pressure, and fluid temperature, plots of the heat transfer efficiency, fluid temperature, and wire temperature versus time are developed. These plots are evaluated to determine if there is fouling potential or an actual fouling problem in the condenser.

A4.7.2 Current Development Status

The Monirex fouling device is a commercially available method for monitoring fouling in petroleum streams. This literature search did not discover any information indicating any previous or proposed research for applying this method to aqueous streams. However, the similarity of this device to the CMU device indicates that it probably could be adapted to this application.

A4.7.3 Sensitivity

Since no evidence was found of this method being used to detect bio-fouling, its sensitivity cannot be determined. Theoretically, as with the other heat transfer resistance monitoring methods (overall efficiency, CMU, turbine backpressure, and LMSC), the sensitivity of the Monirex fouling test method is limited by the thickness of the fluid's viscous sublayer.

A4.7.4 Advantages and Disadvantages

The major disadvantage of the Monirex test is that it has not been used to monitor biofouling in condenser tubes. Thus, its relative merits are unknown. Because of its similarities to the CMU device, it is expected that the advantages and disadvantages of the Monirex test would be similar to those of the CMU device.

A4.8 THE TUBULAR SIDESTREAM REACTOR

A tubular reactor can be used to simulate the performance of a condenser tube. The reactor can be designed to allow accurate measurements of parameters such as fluid flow rate, pressure drop, inlet temperature, and effluent temperature. The reactor can also be disassembled to allow direct examination of the tube surfaces without interrupting condenser operation.

A4.8.1 Description of the Method

Tubular reactors can be designed in a variety of ways for different applications. Bryers et al.⁹ used five different configurations of tubular reactor systems to measure various parameters. In all of these designs, the objective was to simulate the condenser tube's performance in a system in which accurate measurements could be obtained.

Indirect measurements of parameters (such as fluid flow resistance, heat transfer resistance, and wall shear) can be accurately determined in the tubular reactor. The reactor can be opened at various stages of biofilm development to verify and/or correlate indirect measurement data.

A4.8.2 Current Development Status

Tubular reactors are currently being used in laboratory research.^{1,9} This literature search did not reveal any commercial condensers being monitored for biofouling by using tubular reactors.

A4.8.3 Sensitivity

The accuracy and reliability of the tubular reactor will depend upon its ability to simulate the actual performance of a commercial scale condenser tube.

When disassembled for direct inspection, this method should be able to detect any amount of biological growth on the tube walls. For indirect tests, such as monitoring heat transfer, the tubular reactor sensitivity will theoretically be limited by the parameter being monitored. These limits have been discussed for heat transfer and frictional resistance previously (A4.2.1, A4.4.1).

A4.8.4 Advantages and Disadvantages

Some of the advantages for tubular reactors are:

1. Allows direct examination, and hence superior sensitivity.
2. The method is flexible, different parameters may be used.
3. Allows laboratory examination of the biofilm.
4. Can be used to correlate indirect measurements.
5. Reliability of indirect measurements can be checked.

Some disadvantages when using the tubular reactor are:

1. It can be difficult to relate indirect measurements to biofilm thickness because of interference from other fouling materials.
2. If direct examination is employed, the test is discontinuous.
3. The ability of the tubular reactor to simulate actual condenser tube performance must be verified by other methods.
4. Startup of the system may be complicated if it is to accurately simulate the condenser.

A4.9 THE ANNULAR SIDESTREAM REACTOR

Characklis and Bryers^{1,9} are developing an annular sidestream reactor for use in detecting biofouling in condenser tubes. This reactor consists of a stationary outer cylinder and a rotating inner cylinder. Bryers et al.⁹ state that "the rotating annular reactor . . . could provide a more practical, reliable means for monitoring biofouling." No information has been published concerning use of this device. Therefore, it cannot be described here.

A4.10 STANDARD PLATE COUNTS

Standard plate counts are used extensively in cooling tower systems for monitoring biological film growth.^{4,11} The method may be applicable to detecting biofouling on condenser tubes.

A4.10.1 Description of the Method

The Standard Plate Counts method involves sampling the inlet and/or outlet condenser water. Microorganisms in these samples are deposited on a plate and growth is accelerated to a measurable quantity. Correlations between the plate counts and biofilm growth can be used to determine potential or actual biofouling problems.

A4.10.2 Current Development Status

Standard plate counts are often measured during laboratory studies involving biofouling in condenser tubes.¹³ As stated previously, the technique is used extensively for cooling tower systems to determine biofouling control agent effectiveness. This literature search did not reveal any previous research or proposed work to develop the correlations necessary for commercial application to condenser tube biofouling detection or any other research investigations of plate counts as a viable method of detecting biofouling on condenser tubes.

A4.10.3 Sensitivity

This literature search did not reveal any information concerning the sensitivity of plate counts.

A4.10.4 Advantages and Disadvantages

Due to the lack of information obtained, the advantages and disadvantages of plate counts for use in detecting biofouling are not known.

A4.11 MONITORING STREAM COMPOSITION

As a biological film grows on a tube surface, some chemicals are absorbed while other chemicals are discharged. By monitoring the levels of these chemicals, biofilm development can be detected.

A4.11.1 Description of the Method

By monitoring the depletion of nutrients for microorganisms and/or the addition of wastes discharged by microorganisms in the condenser, biofouling can be detected. One of the chemicals which can be monitored is adenosine triphosphate (ATP). ATP is only found in living cells¹³ and is therefore, useful in distinguishing biofouling from fouling due to inorganics, scaling, and corrosion. Other components which have been monitored are organic carbon, nitrogen, proteins, and dissolved oxygen.

A4.11.2 Current Status of Development

No information was found in this study pertaining to the development status of this method.

A4.11.3 Sensitivity

No information was found indicating the sensitivity of this method.

A4.11.4 Advantages and Disadvantages

The primary advantage of monitoring ATP is that it can be used to distinguish biofouling from other fouling types. The primary disadvantage of this technique is the specialized analytical equipment required and the batch nature of analysis. No continuous flow on-line analysis is possible at this time.

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APPENDIX A
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APPENDIX B

TASK 2 SUMMARY REPORT:

PRELIMINARY EVALUATION OF SENSITIVITY AND
FEASIBILITY OF ULTRASONICS FOR
CONDENSER BIOFOULING DETECTION

CONTENTS

<u>Section</u>	<u>Page</u>
B1. SUMMARY OF ULTRASONIC AND ACOUSTIC DATA.	B-3
B1.1 PRESENT MEASUREMENTS BY ULTRASONIC TECHNIQUES.	B-4
B1.2 BIOFILM MEASUREMENT BY ULTRASONIC TECHNIQUES	B-4
B1.3 ACOUSTIC PROPERTIES OF BIOFOULING MATERIALS.	B-5
B1.4 INDUSTRIAL APPLICATION OF ULTRASONICS FOR BIOFOULING MEASUREMENT.	B-11
B2. POTENTIAL ROLE OF ULTRASONIC MEASUREMENT OF BIOFILM THICKNESS IN CHLORINE MINIMIZATION	B-13
B2.1 CHLORINATION EFFECTIVENESS	B-13
B2.2 POTENTIAL USE OF ULTRASONIC THICKNESS MEASUREMENT TECHNIQUES	B-14
B3. RECOMMENDATIONS.	B-16
APPENDIX B REFERENCES	B-18
APPENDIX B BIBLIOGRAPHY	B-19

SECTION B1

SUMMARY OF ULTRASONIC AND ACOUSTIC DATA

B1.0 INTRODUCTION

The second task of the Feasibility of Ultrasonic and Other Methods for Direct Measurement of Condenser Biofouling program was directed at determining the sensitivity of ultrasonic techniques in the detection of biofouling. This task involved a search of available literature for:

1. Sensitivity of ultrasonic techniques in the detection of biofilms.
2. Determination of the acoustic properties of biofouling materials.
3. Correlation of chlorine effectiveness, biofilm thickness, and ultrasonic detection.

The goal of this task was to determine from available literature the feasibility of ultrasonic technology for the detection of biofouling and the advisability of continuing the program with laboratory studies.

This section summarizes the information found in the literature survey. The information is grouped into the following categories: thickness measurements and general applications, biofilm thickness measurement, acoustic properties of biomass, and probability of industrial application.

B1.1 PRESENT MEASUREMENTS BY ULTRASONIC TECHNIQUES

Thickness measurement of metals is one of the most common applications of ultrasonic technologies in industry today. Both resonance and pulse-echo methods of detection are utilized to measure metal thicknesses and detect flaws. The most common applications of the resonance method for thickness measurement are in the 0.05-in. (1270 μm) to 0.175-in. (4445 μm) range with an accuracy of ± 1.0 percent. Instruments using the pulse-echo method of detection are commercially available to measure thicknesses of 0.1-in. (2540 μm) to 10-in. (2.5×10^3 μm) with a ± 10 percent accuracy.¹ Most of these resonance and pulse-echo instruments use frequencies in the 1-5 MHz range.

Measurement of thicknesses in the 50 μm range requires the use of ultrasonic waves with frequencies in the 10-30 MHz range. A metal thickness of 50 μm has been measured with an accuracy of ± 1 percent by the resonance method.² This is the lowest metal thickness measurement recorded in the literature surveyed. Details of the specific equipment used to make this measurement were not found, but it appears that measurements in this range are within the measurement limits of ultrasonic technology.

B1.2 BIOFILM MEASUREMENT BY ULTRASONIC TECHNIQUES

Only one research paper was found concerning the measurement of biofilm thickness by ultrasonic techniques. Loeb and Jarzynski theoretically analyzed the potential of both resonance and pulse-echo methods for biofilm thickness measurement.³ They concluded that the measurement of biofilms in the 10-30 μm thickness range is possible by both pulse-echo and resonance methods at frequencies in the 20-30 MHz range. However, measurements in this range and the accuracy of these measurements have not been verified by laboratory testing.

B1.3 ACOUSTIC PROPERTIES OF BIOFOULING MATERIALS

Loeb and Jarzynski have also determined many of the acoustic properties of a microbial slime (biomass) obtained from a condenser using Chesapeake Bay water for cooling. Their investigations were carried out with an ultrasonic interferometer which uses the pulse-echo technique. Table B1-1 summarizes acoustic and other physical properties of biofouling materials. Of the acoustic properties presented, the acoustic impedance is of great importance when considering the use of the pulse-echo method for biofouling detection. The acoustic impedance value in Table B1-1 is in the same range as other biological tissues of comparable specific gravity, as shown in Table B1-2. Biofouling materials like other biological tissues are composed of up to 98 percent water. The high water content strongly influences the acoustic impedance of the materials and tends to make acoustic impedance vary over a small range. This correlation also confirms the validity of the biomass impedance experimental measurement technique.

The acoustic impedance of biofouling materials is only slightly higher (3 percent) than water. This small impedance difference will make it difficult to distinguish a biofilm-water interface from a metal-water interface because of the weak wave reflection from the interface. This is confirmed by the relative amplitude values of the reflected signals from the biofilm-metal and biofilm-water interfaces shown in Table B1-1. The reflected signal from the metal-biofilm interface is estimated to be 180 to 500 times stronger than that from the biofilm-water interface for the three tube metals considered. This large difference in the amplitudes makes resolution of the weaker signal difficult. The poorer the resolution, the more difficult it becomes to measure the time interval between the reflections. Measurement of this time interval is crucial to accurate thickness measurement. For example, Figure 1 shows a comparison of the relative amplitude and duration of the initial ultrasonic pulse and the reflections from the metal/biofilm and biofilm/water interfaces. The amplitude of the reflection from the metal/biofilm interface is only -3 decibels (db) from the initial ultrasonic pulse, while the biofilm-water

TABLE B1-1. ACOUSTIC AND OTHER PHYSICAL PROPERTIES
OF BIOFOULING MATERIALS^{3,4}

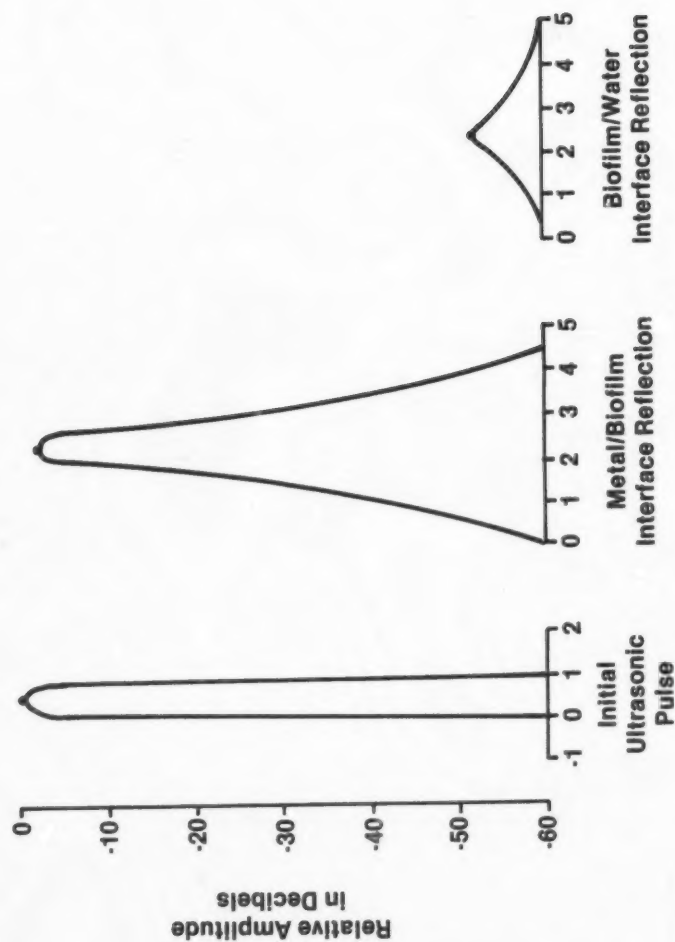
Acoustic Impedance of Biofouling Material	3% Higher than Seawater @ 10 MHz or approximately 1.57×10^5 g/cm ² -sec
Attenuation Coefficient	1.3 db/cm @ 10 MHz
Relative Sound Speed of Biofouling Material (Ratio of the speed of sound in biomass to speed of sound in water)	1.011 @ 10 MHz
Relative Density (specific gravity) of Biofouling Material	1.02

Relative Amplitudes of Ultrasonic Echoes from Metal/Slime and Slime/Liquid Interface for the following Metals:

<u>Metal</u>	<u>Metal/Biofilm Interface Relative Amplitude</u>	<u>Biofilm/Liquid Inter- face Relative Amplitude</u>
Aluminum	0.837	4.6×10^{-3}
Titanium	0.895	3.1×10^{-3}
Stainless Steel	0.937	1.9×10^{-3}

TABLE B1-2. ACOUSTIC IMPEDANCE OF BIOLOGICAL MATERIALS
AND WATER^{3,4} @ 10 MHz

Material	Acoustic Impedance g/cm ² -sec	Specific Gravity
Water	1.52×10^5	1.00
Biofouling	1.57×10^5	1.02
Blood	1.62×10^5	1.06
Brain Tissue	$1.55-1.66 \times 10^5$	1.03
Kidney	1.62×10^5	1.04
Liver	$1.64-1.68 \times 10^5$	1.06



Signal Duration in 10^{-7} Seconds

Figure B1. Relative amplitude and time duration of initial ultrasonic pulse, metal/biofilm and biofilm/water interfaces (theoretical calculations with no signal overlap, based on calculations using 18 BWG 302 stainless steel tube with 50 μ m of biofilm).

reflected signal is -53 db which is a significantly weaker signal. In actuality, the duration of the pulse and reflections begin at the same instant and therefore overlap. The initial pulse can be separated from the reflections by increasing the transducer metal thickness and therefore adding a time delay. However, the reflected signals cannot be separated and will result in a superimposed and distorted signal curve as shown in Figure B2. This is the type of superimposed curve that might result from the proposed laboratory investigations. To measure the thickness of the biofilm, the time between the reflected signal amplitude peaks (as shown in Figure B2) must be discernable. If the biofilm/water interface reflected signal is not sufficiently strong, then its amplitude peak may not be distinct. Biofilm thickness measurement may not be possible if this occurs. However, it is still conceivable that a change in signal curve shape can be correlated with the accumulation of biofouling materials.

Other acoustic properties important to ultrasonic thickness measurements by the pulse-echo method are the attenuation coefficient and the speed of sound through the biofouling material. Attenuation is the measure of the sound energy dissipated as it passes through a material. The attenuation coefficient of biofouling materials at 10 MHz is 1.3 db/cm as compared to 0.3 db/cm for water. Unfortunately, this higher attenuation adds to the problem of detecting the biofilm-water interface. The higher the attenuation coefficient, the weaker the reflected signal from an interface will be. The speed of sound is only slightly higher in biofouling materials than in water and will not significantly impact the measurement of biofilm thickness.

The pulse-echo method of thickness measurement is very dependent upon the acoustic impedance of metal and biofouling materials and the ultrasonic wave length. The resonance method of thickness measurement correlates biofilm thickness with the shift in the tube metal resonance frequency. Therefore, the resonance method of biofouling detection is much less dependent upon the individual acoustic properties than is the pulse-echo method.

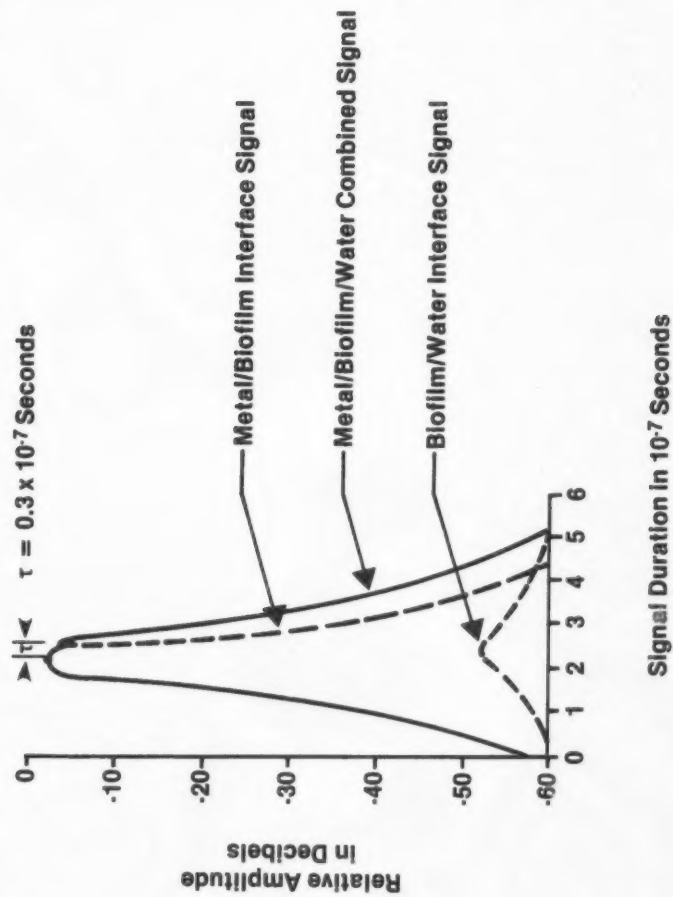


Figure B2. Predicted distortion caused by the overlap of the time duration of the reflections from metal/biofilm and biofilm/water interfaces (theoretical signal curves shown with dashes, τ is the time lapse between interface reflections that must be measured in order to detect the biofilm).

B1.4 INDUSTRIAL APPLICATION OF ULTRASONICS FOR BIOFOULING MEASUREMENT

Both resonance and pulse-echo methods of ultrasonic thickness measurement are used industrially. However, the literature survey did not reveal any applications similar to that required for biofouling detection. Discussions with ultrasonic equipment suppliers indicate that commercially available equipment may require additional hardware development before either method can be successfully applied to an industrial biofouling application.

The data presented above indicates that both resonance and pulse-echo methods are capable of measuring biofilm thicknesses of less than 50 μm . The accuracy and sensitivity of both methods are dependent upon different physical parameters. These differences may determine the true potential of the individual method for industrial biofouling applications.

The pulse-echo method is extremely sensitive to the acoustic properties of the materials involved. It is therefore a good method for the determination of the acoustic properties of materials. As previously discussed, ultrasonic pulse and reflected signal resolution is a major problem with this method and may limit its potential for industrial biofouling measurement application. Further investigations in this area are required before a definitive answer to the probability of success using pulse-echo methods for biofouling detection can be determined.

On the other hand, the resonance method is sensitive only to the resonance frequency of the metal. It is not dependent upon the biofilm acoustic properties. This method has been used to measure metal films approximately 50 μm in thickness. Based on the limited data available, the resonance method appears to have a high potential for biofouling detection application. This again must be confirmed with actual operating experience or testing.

Although the measurement of thin biofilms is within the capability of ultrasonic technology, the actual method and equipment requirements for industrial application are yet to be determined. It is recommended that further

testing of commercially available equipment be undertaken to more completely assess the true potential of ultrasonic technology.

SECTION B2

POTENTIAL ROLE OF ULTRASONIC MEASUREMENT OF BIOFILM THICKNESS IN CHLORINE MINIMIZATION

Regulations for steam electric generating plant effluents are set at a maximum of 0.5 mg/l and an average of 0.2 mg/l of free available chlorine (FAC) to be discharged for no more than 2 hours per day per generating unit. Some EPA regional offices have set stricter chlorine effluent limits for individual plants through the National Pollution Discharge Elimination System (NPDES).⁵ The stricter limits are to be met unless the plant is unable to operate at or below this lower level and still maintain condenser performance. The proposed New Source Performance Standards require zero discharge of total residual chlorine (TRC). Where it is demonstrated that biofouling cannot be controlled with no discharged TRC, a maximum concentration of 0.14 mg/l will be allowed and will be limited to two hours per day per discharge point.⁶ In an effort to comply with these regulations many utilities have initiated "chlorine minimization" studies to determine if and under what conditions biofouling can be controlled at the low chlorine concentrations and within the 2-hour time limit. This section will focus on defining the biofilm thicknesses for which low level chlorine concentrations can be effective and relate this to potential ultrasonic measurement range.

B2.1 CHLORINATION EFFECTIVENESS

Studies using pilot condensers in parallel with operating condensers have been used to evaluate the effectiveness of chlorination for biofouling control.⁷ These studies compared dried biomass accumulation with chlorine treatment levels. In order to relate the dried biomass accumulation

(g/cm²) to a biofilm thickness, certain assumptions must be made. If the density of the biomass is assumed to be 1.02 g/cm³ and the biomass is assumed to be 97-98 percent water, an average film thickness range can be calculated. The maximum film thickness above which low level (<0.5 mg/l) chlorination has no appreciable effect on film growth is approximately 500 μ m (0.02 inch).⁸ Chlorine residuals below 0.2 mg/l FAC were shown to have no effect on controlling biomass accumulation regardless of biofilm thickness. Complete control of biofilm formation was achieved at a chlorine concentration of 0.4 mg/l in the effluent. At this chlorine level, slimes were maintained at less than 50-75 μ m and no degradation of condenser heat transfer coefficient was observed. This calculation of biofilm thickness is sensitive to the assumed percent water content of the biomass. However, this thickness range closely correlates with the 50 μ m thickness below which no degradation of heat transfer coefficient occur as discussed in the Task 1 Summary Report.⁹

Correlations of biofilm thickness before and after chlorination have been presented by Characklis.⁷ His results indicate that a 76 to 80 percent removal of biofilm thickness can be achieved if the biofilm thickness is less than 50 μ m when chlorination begins. With initial biofilm thicknesses at 100 μ m and 250 μ m, removal was reduced to 60 and 8 percent, respectively, at comparable chlorination levels. These data are consistent with the widely accepted theory that chlorination effectiveness is directly related to the diffusion of the chlorine through the biomass. As biofilms get thicker and more complex in structure, chlorine penetration is impaired and its effectiveness as a biofouling control agent is reduced. In order for chlorine to be used effectively (minimized), biofilms must not be allowed to grow to thicknesses >50 μ m.

B2.2 POTENTIAL USE OF ULTRASONIC THICKNESS MEASUREMENT TECHNIQUES

Chlorine minimization involves careful consideration of many variables such as chlorine demand for both nonbiofouling and biofouling materials, duration of chlorination period, type of chlorine utilized, condenser flow

patterns, and thickness of biofouling materials. The thickness of the biological accumulation has a great effect on many of these variables. The measurement of a biofilm in the initial (or inductive) growth phase ($<50\text{ }\mu\text{m}$ thick) would greatly enhance the development of an effective chlorine minimization program.

By comparing the data presented in Sections B2 and B3, a correlation becomes apparent. The biofilm thickness range ($<50\text{ }\mu\text{m}$) in which low level chlorination is most effective can potentially be measured by ultrasonic techniques. However, the sensitivity of ultrasonics to this biofilm thickness range is yet to be confirmed. It appears that ultrasonic thickness measurement has the potential of becoming an effective tool in the chlorine minimization effort.

SECTION B3

CONCLUSIONS/RECOMMENDATIONS

Currently there are no commercially proven methods for detection of thin (<50 μm) biological films in utility condenser tubes. Measurement of these thin biofilms is necessary to effectively minimize chlorine addition and maintain condenser heat transfer performance. The data presented in the previous sections indicate the feasibility of ultrasonic detection and measurement in this application. Ultrasonic technology appears to be the only technology that can potentially measure biofilms in the <50 μm range. Unfortunately, the conclusions above are drawn from a limited data base. Most of the data are the result of theoretical evaluations and preliminary laboratory studies. Ultrasonic technology is in the early developmental stages for this application. Many major issues concerning this application of ultrasonics still need resolution and will require laboratory experimentation before the true potential of ultrasonics can be evaluated.

The actual ultrasonic technique that will most accurately measure biofilm thickness is not known. Both pulse-echo and resonance methods of thickness measurement have been shown to have potential. The pulse-echo ultrasonic equipment is readily available in the frequency ranges required for the measurement of biofilm thickness. Industrial application of pulse-echo thickness measurement will require resolution of many problems. However, this technique is the most sensitive to the acoustic properties of materials and is the best method for laboratory determination of these properties. The resonance method of thickness measurement will require extensive equipment development for an industrial application. It does appear to have a potential for accurate measurement of thin biofilms. The resonance method cannot be used for determination of the acoustic properties of materials since it is dependent only on the resonance frequency of tube metals.

Literature surveys have indicated that there is little known about the acoustic properties of biofouling materials. The Task 3 effort in this study program is designed to define the acoustic properties of biofouling materials using state-of-the-art ultrasonic equipment. This laboratory evaluation will use the pulse-echo method to determine the acoustic impedance of biomass. In the course of these experiments, many of the issues concerning ultrasonic thickness of biofilms will be addressed. The most significant of these issues are:

1. Can commercially available state-of-the-art ultrasonic signal processing equipment measure the time interval between reflected signals?
2. Can ultrasonics reliably and accurately measure biofilm thickness in the $<50\text{ }\mu\text{m}$ range?
3. Can ultrasonic equipment be adapted to the power plant environment and provide meaningful outputs?
4. What acoustic properties vary significantly from site to site?

Task 3 will not resolve these issues but will be a first step in the development of solutions. This task will also provide guidance to EPA concerning the merits and potential of further development of ultrasonics in this application. State-of-the-art ultrasonic equipment is available to the program from EPA Contract No. 68-02-3163 and will minimize the cost of the laboratory studies.

For these reasons, it is recommended that Task 3 be initiated as originally planned. It should be recognized that this is a first step toward evaluating the true potential and practicality of ultrasonic technology in the measurement of biofilm thicknesses.

APPENDIX B REFERENCES

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